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A Balloon-Borne Tether and Reeling System for Multiple Drop Tests*

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Abstract

Microgravity is a fascinating environment with many and varied applications over the realms of engineering and science. However, it is challenging to produce low gravity environments suitable for scientific testing on Earth. All attempts nowadays are expensive and time consuming. This project aims to show that low gravity can be reached at lower costs than current approaches such as parabolic flights or drop towers. This project is a feasibility study of a technique that could be used to create a low gravity environment. If this project can demonstrate that the selected approach is practical, it can be scaled up for larger payloads or longer periods of low gravity.

The approach used is to drop a payload off a high altitude balloon. During the drop, the payload is connected to the balloon gondola via a tether which is unreeled from an ordinary fishing spinning reel. The drop is decelerated using the internal brake of the fishing reel. As soon as the payload comes to a halt, it is reeled back up to the gondola and is ready for the next drop.

The project's name is reel.SMRT ("real smart"). It was realised within the BEXUS (Balloon Experiment for University Students) programme, which is made possible through a bilateral Agency Agreement between the German Aerospace Center (DLR) and the Swedish National Space Board (SNSB). The Swedish share of the payload has been made available to students from other European countries through a collaboration with the European Space Agency (ESA). The student group designing and building this experiment consists of eight students originating from eight different countries. All of them were enrolled in the Erasmus Mundus sponsored SpaceMaster programme.

The reel.SMRT system was fully functionally tested and flew on-board BEXUS-09 in October 2009. During the flight, the safety guide was unreeled, the dropped payload was reeled up and then a drop was successfully performed. However, due to an unforeseen event, the dropped payload did not brake correctly and snapped the line, so was unable to be reeled up to obtain the acceleration data. Despite not achieving full functionality, the reel.SMRT experiment demonstrated that a low gravity platform utilising a tethered dropped payload is theoretically possible and could operate in the harsh environment of the stratosphere. The system, however, is unable to provide a measure of the quality of the reduced gravity until the dropped payload and its acceleration data is recovered.



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Of all reel.SMRT's sponsors, ESA not only supported the team for travel and accommodation for workshops and the campaign but have gone above and beyond this to by further sponsoring the team with a substantial monetary contribution for components and testing. For this, reel.SMRT will forever be grateful and cannot give thanks enough.

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We are most appreciative of Ignca Jandak's efforts in assisting with the population and testing of the MAIN Payload PCBs, at a critical time in our project when manpower was so important.

Previous team members Mark Fittock and Jürgen Leitner left the team when they could no longer participate fully in the project. Nonetheless, Mark has continued to provide valuable advice, feedback and help for reel.SMRT in the role as a team mentor. Jürgen continues to maintain the web page for the team and was invaluable in obtaining sponsors.

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Last but certainly not least, the team greatly appreciates the input and support of their supervisors at LTU, Alf Wikström and Kjell Lundin, whose feedback and contribution has been most valuable.

To everyone who made this epic and incredible journey possible, we say:

'Thanks! And So Long to the FISH!'



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1 INTRODUCTION

The reel.SMRT Project was a system launched on a Stratospheric Balloon in October 2009 as part of the BEXUS-9 flight of the REXUS/BEXUS programme. Through this programme, reel.SMRT aimed to investigate the feasibility of a balloon-based reduced gravity environment platform, capable of multiple tests in a single mission. The vision is that the platform may be ultimately up-scaled to provide a viable alternative to parabolic flights and drop towers. The system has the potential to drastically increase the maximum drop lengths of such systems, along with more frequent drops and a greater number of drops in a single mission. The reel.SMRT system was designed to also have secondary applications for balloon experimentation. By lowering a capsule, it is possible to take measurements of the atmospheric conditions further from the gondola, increasing the sampling range for sensors. Additionally, the tether has possible applications as a safety line for other experiments such as UAV experimentation. This means that the mission, rather than having a purely scientific objective, was an investigation of an enabler for future experiments. In the Stratosphere, a balloon that can drop, reel down and reel back up a payload, and perform this multiple times, truly expands the possibilities for balloon experiments.

A key design driver for the system was its ability to be up-scaled to eventually be extended to cover distances of hundreds of metres and more. Thus in this investigation, what was tested was the feasibility of such a system. Data obtained from the mission was intended to be used to evaluate the performance extended over larger scale missions. Therefore, the reel.SMRT system is an initial prototype of a system that has the potential to provide a viable commercial alternative to microgravity experimentation and enabling balloon tethered experimentation.

1.1 Document Overview

This document commences with an introduction to the mission, objectives, scientific background and support. The system requirements are defined in Chapter 2. Chapter 3 begins with an introduction to the experimental modes, an overall system description and list of budgets and component lists. The interface definitions are then displayed, followed by the comprehensive descriptions and analysis of subsystem preliminary designs. The preliminary simulation investigation into the system feasibility and performance is also encompassed by this chapter as is the preliminary post-processing plan. The reviews and tests are covered in Chapter 4, including the recommendations from the experiment selection workshop, and the subsystem test plans and decision flow chart. Chapter 5 encapsulates the project planning approach including the work breakdown structure, time schedule and resource estimation. Here, the risk management plan is also presented with the most critical risks analysed and addressed. Chapter 6 explains the outreach programme, including tasks to date and future plans. Chapter 7 briefly describes the interference effects between the reel.SMRT experiment, the gondola and the other experiments of BEXUS-9. The



launch campaign plan and execution is described in Chapter 8, including requests for resources, inputs to the FRP and pre and post-flight activities. Chapter 8 also delves into the diagnostics of the flight, before describing the results obtained and discussing the lessons learned. The document concludes with a statement of the current status of the experiment. An appendix for each subsystem is attached to the document as a separate file.

1.2 Experiment Objectives

The primary objective of the reel.SMRT system is:

Obj.P.1 *To investigate the feasibility of producing a reduced gravity environment on a balloon payload in a recoverable manner and perform this multiple times.*

The secondary objectives of the reel.SMRT system are:

Obj.S.1 *To achieve a versatile line and reel system for increased sampling height range and capability for tether-based applications.*

Obj.S.2 *To educate students about the role and potential of balloon based experiments.*

1.3 Scientific Background

1.3.1 Previous Similar Studies

In order to overcome difficulties of reduced gravity condition testing, reel.SMRT brings together concepts from previous studies and applications. In this way, not only is the project aided by the resources compiled by others but it also highlights the possible applications and the desire of researchers for a system such as reel.SMRT.

1.3.1.1 Capsule Drops from High Altitude Balloons

Much research has been conducted into the possibilities of short reduced gravity periods enabled by dropping from high altitude balloons. A simple dropping capsule was designed and tested by High Altitude Reduced Gravity Vehicle Experiments (HARVE) (1). This team was able to achieve seven seconds of reduced gravity time from a height of ~24,382 metres. This was without any mitigation of aerodynamic perturbations, similarly to reel.SMRT. A schematic of the HARVE dropped capsule is shown in Figure 1.1.

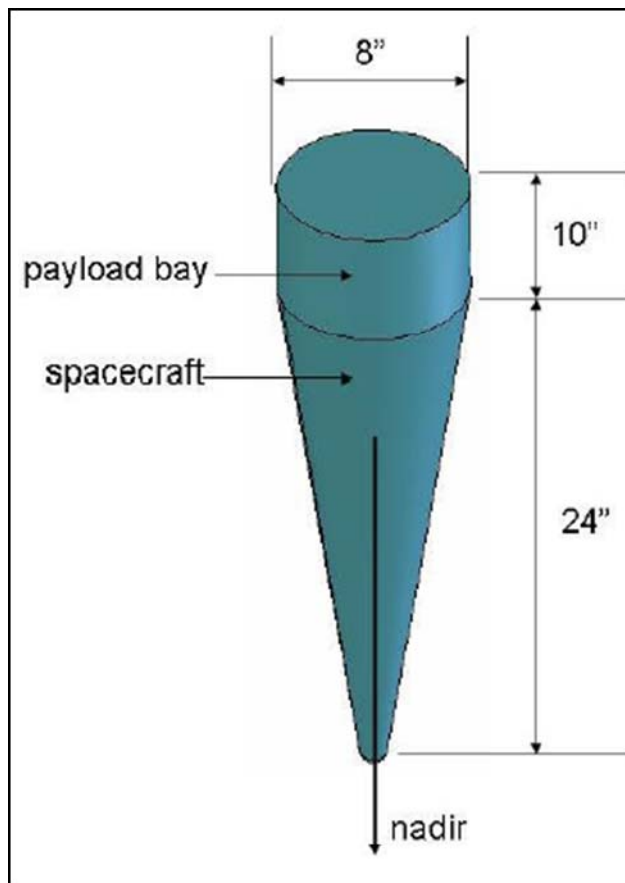


Figure 1.1 Schematic of the HARVE craft (1)

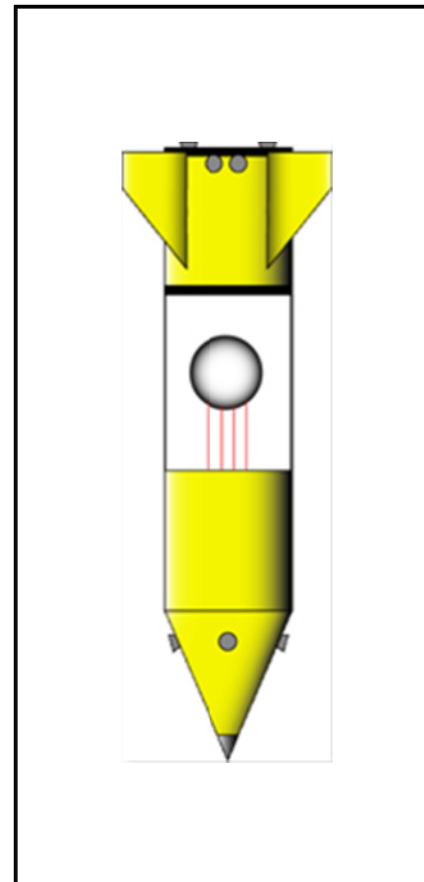


Figure 1.2 Sawai Lab's Vehicle and Microgravity Experiment Unit (2)

There are methods to damp these influences upon experiments within modules that are travelling through the upper atmosphere. Similar to the HARVE experiments, Sawai Lab have been conducting tests of a capsule (2) that is able to re-enter the lower atmosphere much like a space-plane. This module is also designed for reduced gravity testing but also has the added feature of perturbation mitigation via the use of a number of gas jets that supports an experiment away from the structure of the dropping body.

1.3.1.2 Reel System

Another experiment that embodies many similarities to the reel.SMRT system was developed by a group of Japanese researchers. This experiment fulfils the same objective to increase the sampling height range of experiments on board high altitude balloons. This system was developed specifically for observing stratospheric vertical microstructures and was a slow reel up and down system (4 reel-down and reel-up cycles of 600m on a high altitude balloon flight) (3). However, this system did not aim for low gravity conditions.

YES2 (4) was an ambitious experiment for students that released a dropped payload to 30 km below an orbiting reel system. Although reel.SMRT is not unreeling to the same distances or in Space, a review of this project has been conducted and useful caveats have been discovered regarding line tension and braking systems.

Two members of SMRT ('The SpaceMaster Robotics Team') conducted the xgravler experiment (5) onboard the HALE balloon (6) in 2008. This project, known as 'REEL-E', had the restriction to use LEGO components and thus was a limited test for a short drop and reel system. xgravler appeared to have ran the experiment during the flight but when data retrieval was conducted, the acceleration data was a constant error value (7).

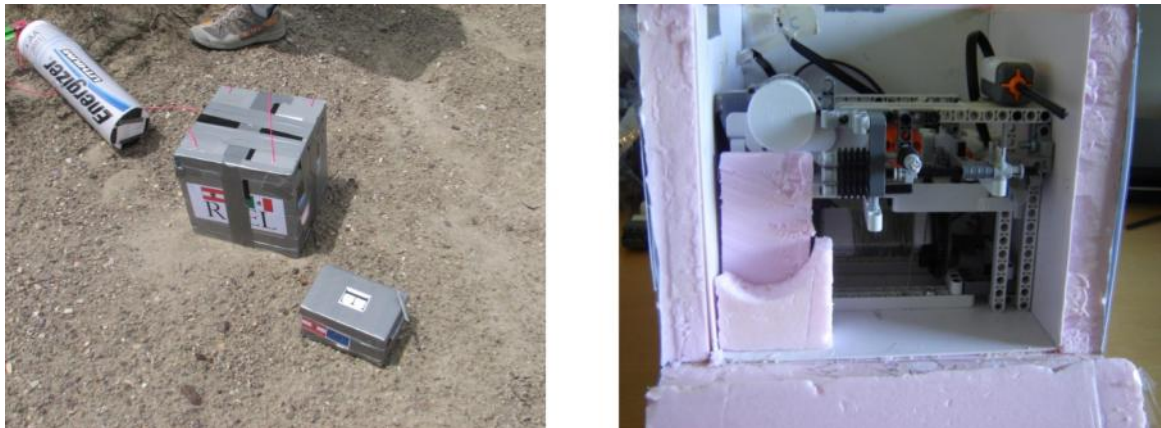


Figure 1.3 REEL-E Attached to Gondola and REEL-E Interior Mechanics

1.3.2 Future Applications

Although some microgravity experiments require longer periods of reduced gravity environment than is possible through a drop tower or high altitude balloon drop, there are a number of fields that take advantage of current techniques and could feasibly fly onboard a reel.SMRT system. Short duration fluid effects, such as microdroplet production (8), foam attributes (9) and biphasic fluid investigation (10) are applicable. Loosely also within fluid experimentation are the many biomedical studies that undertake microgravity investigation. Combustion experiments which are not allowed on board parabolic flights could still use the safety net of the reel.SMRT tether system to still conduct their important research. Biological experiments such as the behaviour of fish in reduced gravity environments (11) can also be conducted on an up-scaled version of reel.SMRT. Crystallisation and metallic microstructure formation (12) are also hot topics in the microgravity field and are ideal for short drop testing. reel.SMRT is particularly useful in the above fields because of the possibility for high amounts of repetition of the drops and is an alternative to most drop tower experiments that may not necessarily require the accuracy of drop tower systems.



1.3.3 Reduced Gravity System Cost Comparisons

It is important for reel.SMRT to draw comparisons between the different low gravity options available. This is largely been covered in section 0 which compares conditions to those of similar systems. Due to the huge variety of low gravity conditions available, one of the most important comparisons for a potential experimenter is the cost for applicable options.

reel.SMRT itself is most comparable to drop tower and parabolic flight conditions due to the duration and repeatability of low gravity conditions. Sounding rockets (603 €/kg for the Indian RH-630 (13)) and orbital options such as the space shuttle (30,000 USD/kg or ~21,500 € for microgravity experiments (13)) tend to be an exclusive option in comparison to the balloon drops envisaged by the reel.SMRT system. This is because an experiment that requires these conditions is unlikely to find short duration conditions a feasible alternative.

Parabolic flights in Europe cost approximately 750,000 € for a three flight day campaign each of 31 parabolas including support of the flight but not scientists' expenses (14). For a regular flight, there are 14-15 experiments on-board with an average mass of 2,900 kg (including experimenters). The total microgravity time comes to 10 minutes per day. Therefore, each experiment has 10 minutes of low gravity time (10^{-2} g for about 50,000 € per experiment). Most experiments require only minimal changes from laboratory equipment to meet safety requirements.

For Fallturm in Bremen, optimistic pricing gives a cost of 5,800 € per drop (when drops are conducted in series of 10 or 15 for an experiment) (14). So for an experimenter using ten drops, they will be paying 58,000 € (or more) for the drop campaign. The drops of 4.7 sec (9.3 sec with catapult) are at 10^{-5} g or better. These costs include the accommodation and support for the scientists. When experiments are conducted in the drop tower, they most often need to be custom built and this increases the costs for those using the drop tower facilities.

Although reel.SMRT is only able approximate costs for a future system, an approximate analysis has been conducted and is presented here. As a caveat, the costs of constructing a larger reel.SMRT system have been estimated and the costs are only indicative of true future costs.

Using the Indian Space Research Organisation's balloon costs of 45 €/kg (13) for a 500 kg capacity balloon flying to 40 km altitude (13), the current reel.SMRT design will take 2 kg (with the reel.SMRT payload weighing 20 kg) at a total cost of 1,125 € plus the cost of the construction of the reel.SMRT system of approximately 14300 € (see Appendix 2.1), if on board a balloon with other experiments. This cost does not include any scientists' expenses nor the expense to construct an experiment that is suitable for use in balloon conditions.

The current reel.SMRT system cannot be extrapolated to a series of 20 on board a 500 kg balloon due to risk of entanglement. However, if the whole 500 kg were used to launch a single large reel system, it would be possible to have a 100 kg dropped payload (with a considerable braking distance). It is also envisaged that any experimenter is likely to require a small degree of engineering support, this

would be estimated at 0.1 man years, at a cost of 60€ per man hour, this would be approximately 10,000€ The cost for total flight would be approximately 32,500 € (including 22,500€ for the balloon). This does not take into consideration the development costs required to generate a larger version of the system.

It would be possible with larger balloons that the dropped payload could be increased further. If such a much larger system were used, it would be possible to modularise the system to decrease the costs to the experimenters for hardware development. With the drop distances possible along with larger weight capacity a reel.SMRT style system could be a competitive option in the world of reduced gravity experimentation.

1.3.4 Benefits of the reel.SMRT System

The reel.SMRT system has a number of benefits that make it a viable alternative for low gravity testing in the future. The quality of low gravity expected is not to the level of drop towers or specialist rockets, nevertheless, the dropping of a payload from a balloon gives researchers new opportunities. The versatility of the system to act as a low gravity platform, sampling platform or safety tether is also an advantage. Comparisons to currently available systems are described in Table 1 Comparison between parabolic flights, drop tower and reel.SMRT systems

Parabolic Flight	Drop Tower	reel.SMRT Concept
Advantages		
• Interaction during tests • Interaction between tests • No extreme temp or pressure • Fun and Public Outreach • Variable gravity conditions • Transportable	• High quality reduced gravity • Interaction between tests • Proven and respected • Lag time and accessibility	• Payload Versatility • Multiple drops • Potentially relatively low-cost • Many potential operators • Variable gravity conditions • Transportable • Vacuum & thermal enviro. • Versatile system: modes • Transferable tech: space expl. • Very large drop time
Disadvantages		
• Low quality reduced gravity • Variable gravity quality • Cost	• Impact forces • Vacuum environment • Fixed location • Cost and application time	• Unknown quality of gravity • Vacuum and thermal environ. • No physical interaction • Power and Mass Budgets limited by balloon capacity

Table 1 Comparison between parabolic flights, drop tower and reel.SMRT systems



1.3.4.1 Location Flexibility

A major benefit of conducting microgravity experiments from balloons is that there are many such locations from which they may be performed. High quality drop towers are limited to Fallturm (15) in Bremen, Germany, Micro-Gravity Laboratory of Japan (16) and the three towers (17) (18) (19) run by NASA in the USA. This is particularly of interest to those countries that are not close or do not have access to these facilities such as Australia and the South American nations.

1.3.4.2 Availability

Not only are these drop towers limited to location but availability is a significant issue for many researchers wishing to investigate microgravity effects. High altitude balloons are readily available in many countries (20) and in order to use such a system all that is required is the construction of the reeling system and the adaptation of the experimental payload. Following feasibility studies, it is envisaged that such systems could be constructed very quickly and be reusable (unless they are lost or damaged during flight, which would not occur in the course of normal operations).

1.3.4.3 Frequency of Drops

Another issue for many researchers is the number of experiments they can realistically conduct at drop tower locations. For ZARM in Bremen only 15 drops of 4.74 seconds are feasible in a normal weeks operation (15). In order to achieve high levels of microgravity, these facilities must evacuate the chamber of air to reduce air density and as a result, the perturbations on the dropped capsule due to drag. Through the use of a drop and reel system such as is being developed by the reel.SMRT team, it would be possible to conduct more than 100 drops in a single flight (depending on drop parameters and battery capacity).

1.3.4.4 Quality of Reduced Gravity

The simulations currently investigated by reel.SMRT (refer to Section 3.9 'System Simulation') show that it should be possible to see an achievable quality of 10^{-3} G's with the reel.SMRT system. With our current on-board sensor package, this is also the best resolution that may be achieved. Techniques such as using gas jets (2) or other damping techniques to reduce perturbations being transmitted to an experiment from the dropped capsule could be implemented, if required, in further design iterations. In the future, it is hoped that considerable improvement and refinement will be made upon the quality. This compares favourably to the 10^{-2} g's that are created during parabolic flights (21).

1.3.4.5 Environment

The Stratospheric environment has been singled out as a significant detractor of attempting microgravity experiments from high altitude balloons. However, there are experiments for which this environment is advantageous. Due to the similarities of the Stratosphere to the Martian atmosphere, experiments have previously been conducted on balloons to investigate their effectiveness in such



an environment (22). This can also be taken one step further by reel.SMRT; as the system allows for not only free-fall drops but also descents controlled by reeling down, it is possible to replicate Mars gravity level whilst in the low density atmosphere. It is also possible, by controlling this reel down speed, to simulate gravity conditions further from Earth and around other solar systems.

1.3.4.6 UAV tether drops

A future application upon the scaling up of the reel.SMRT concept would be to tether experiments wishing to drop from the balloon. This will allow drops of payloads with minimal interference compared to an ordinary drop. However, it would be possible over the duration of the balloon flight to drop and recover multiple times; giving experimenters the ability to perform a wider variety of tests or to refine their data. This would be a possibility from lower altitude balloons as well for experiments such as SpaceFish (23) and Icarus (24).

1.3.5 **Parabolic Flight Comparison**

For the best comparisons to other low gravity systems, reel.SMRT endeavoured to launch its accelerometers on a simplified FISH-based system in order to record data from parabolic flights and drop towers, where possible. The validity of the scientific output of this BEXUS project would be vastly improved by such a test, for which systems could be directly compared using the same sensor suite with accelerometers of the same type and calibration. In such a case, reel.SMRT would envisage performing such a test as close to the BEXUS-9 flight as possible. The reel.SMRT system would be easily adapted to such a flight, requiring only a very small area, approximately 10 cubic centimetres to house the sensor suite system, or a maximum of 50 cubic centimetres if the entire FISH were to be flown. As the FISH will be flight ready for BEXUS, a system could be delivered to a parabolic flight campaign at short notice. This is because the FISH already conformed to the requirements of parabolic flights, with only minor structural modifications needed. As the system can operate independent of a user and external power, it would also not be necessary for a team member to be present.

The reel.SMRT team applied to the ESA “fly your thesis!” parabolic flight campaign with the goal to get a chance to fly the sensor package of the FISH onboard the zero-g aircraft. Unfortunately, this application was not successful, and with the loss of the FISH during the balloon flight, data could not have been verified in this way.

1.3.6 **Future Possible Developments**

There are a few potential upgrades that will be investigated by reel.SMRT. These focus on three major issues hindering possible experimenters not developed in the current iteration of this system. These are experiment power, total drop length and dropped payload weight.

Several options are under consideration for how to increase the power supply of the dropped payload whilst attempting to not dramatically increase the weight. The first option which was considered but decided against for this iteration of reel.SMRT, due to risk, complexity and cost of development, was to use a cable



connecting the main payload to the dropped payload. Two options were considered, having a second line delivering power and delivering power directly through the tether itself. The first was dismissed due to the risk of entanglement and possibility of hindering the dropped payload's descent. Transmitting power through the line was an appealing option but a few issues were quickly identified that discouraged its use. It would require an insulated line with similar properties to a fishing line. This method also sees some issues with small current being possible in the line and large resistances for the length of line.

As the issues with transmitting the power by cable over this distance, a few possibilities have been tagged for investigation. In light of the issue with using a direct connection, wireless transmission is being considered via laser or microwave. These both have the benefit in the stratosphere of being made more efficient due to the lower particle density decreasing dispersion and atmospheric absorption. Another option combines using the tether for transmission and the laser concept would be to use fibre optic cabling and transmitting energy via this. Another option worth considering and most likely the easiest to implement would be to use a rechargeable battery in the dropped payload that can be recharged at the main payload thus minimising the battery weight of the dropped payload.

1.4 Scientific Support

Kjell Lundin and Alf Wikstrom both supervised this experiment within LTU. They have both spent many years involved in the Space Industry of Kiruna (ESRANGE, IRF and IRV). Currently they are employed by IRV part time to supervise student projects for balloon and rocket flights (previously including BEXUS(24), REXUS and EXUS launches).

1.5 Team Organisation

The reel.SMRT Project team is comprised of seven students from the 'Erasmus Mundus Joint European Master in Space Science and Technology', or 'SpaceMaster'. There is one Round 3 member, who began in his second year of the program and six Round 4 members, who began this project in their first year of the program and studied at LTU in Kiruna, Sweden, from February to June 2009.

Each of the six Round 4 members were expected to do equal amounts of work to achieve the best outcome for the project. The workload required was dictated by task allocation and so was outcome driven (tasks achieved) rather than time driven (hours per week). This was because these members are enrolled in a 15 ECTS point subject at LTU for this project.

The tasks were delegated to each subsystem from the Project Manager. Within each subsystem, the Subsystem Manager was responsible to the Project Manager for the implementation of their tasks. This means that the Subsystem Managers delegated tasks within their subsystem and ensured their timely completion. The team was structured so that the Subsystem Managers and the Project Manager were all located in Kiruna for ease of communication and control. The structure of the team, and their communication links to the facilitation and support elements, are shown in Figure 1.4.

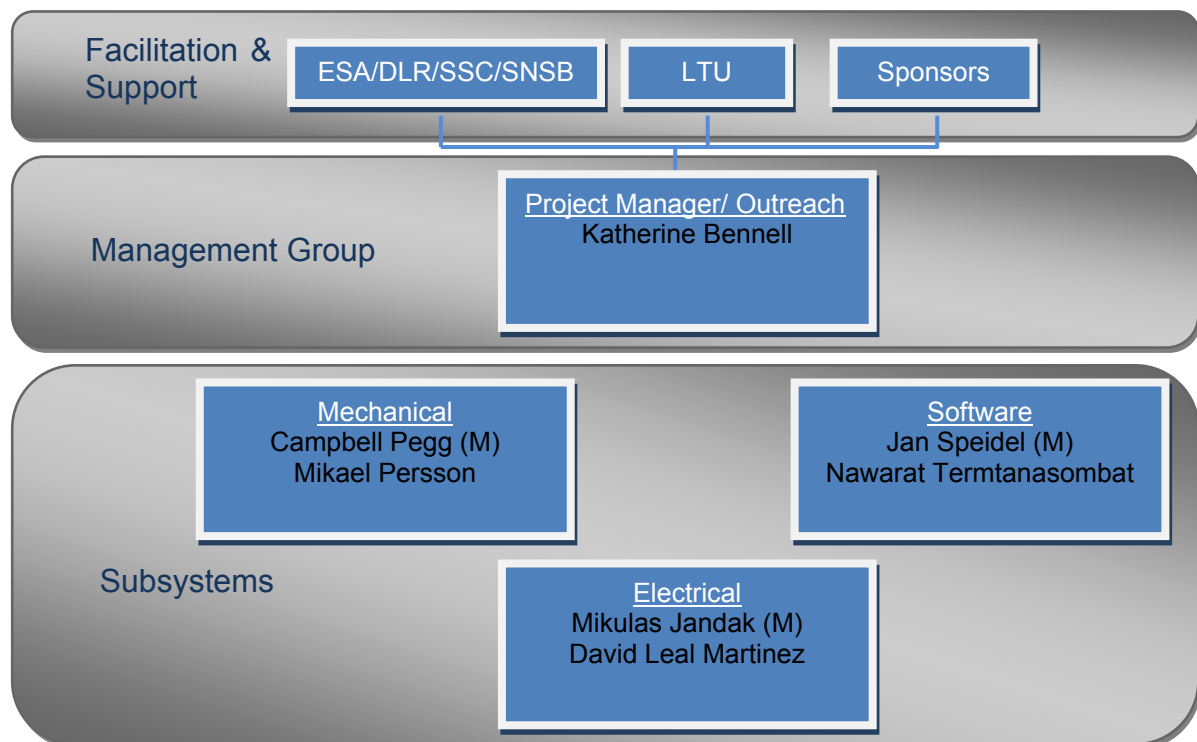


Figure 1.4 Original Team Structure for the reel.SMRT Project

1.5.1 Katherine Bennell – Project Manager



Figure 1.5
Katherine Bennell

Katherine Bennell, from Australia and the UK, is a Round 4 SpaceMaster student and the Project Manager for the reel.SMRT project. She holds a Bachelor of Engineering in Aeronautical and Space Engineering (Hons) as well as a Bachelor of Advanced Science majoring in Advanced Physics from the University of Sydney, Australia. Katherine conducted her thesis on Microcombustion. She has work experience with the Royal Australian Air Force, conducting research on the NASA STEREO space antenna impedance modelling as well as

High Redshift Galaxy spectral analysis, a NASA satellite simulation platform and a NASA/International Space University project on Martian cave habitation feasibility.

Katherine has a background in management and leadership, with experience in sports, defence and engineering projects. She commenced her final year of studies at Cranfield University in October 2009 with a thesis on biomimicry for solar sail design.

As Project Manager, Katherine planned and directed the project, as well as performing a systems engineering role. Key tasks included defining system objectives and their verification, estimating work and duration and determining overlapping tasks. Directing involved task delegation to subsystems and delegation of interface responsibilities, both technically and for the SEDs. This means that Katherine aimed to ensure that tasks were performed at a sufficient standard to achieve the project objectives. As such, she also reported on the tasks and ran the bi-weekly meetings where she reviewed the progress and completed work and resolved team issues. Katherine also worked on drafting sponsorship applications and agreements, monitoring resources and cost budgets and conducted the FISHy design competition. As manager, she also acted as the link between the team and the supporting organisations of ESA, DLR, SSC, SNSB and LTU.

1.5.2 Campbell Pegg - Mechanical Subsystem (Manager)



Figure 1.6
Campbell Pegg

Campbell Pegg, from Australia, is the manager of the Mechanical Subsystem and a student in the Round 4 SpaceMaster Programme. In 2007, Campbell completed a Bachelor of Aeronautical Engineering with First Class Honours as well as a Bachelor of Advanced Science majoring in Advanced Physics and Advanced Mathematics from Sydney University, Australia. He completed his honours thesis in combustion on droplet evaporation in turbulent flow. Campbell conducted his internship with DLR on rocket propulsion and was his team leader and structures

subsystem lead for the SpaceMaster Cansat Project. Campbell has also achieved his commission as an officer

through the Australian Defence Force, and has since led a platoon of infantry soldiers for two years. Campbell currently studying at the International Space University Space Studies Program at NASA Ames, where he is managing the Engineering Division in an investigation into the feasibility of using Martian Caves in human exploration.

In the reel.SMRT project, Campbell was responsible for the Mechanical Subsystem. This means that he delegated tasks within his subsystem and ensured that they were carried out in a timely manner and to an acceptable standard. Campbell was also directly responsible for the mechanical design, construction and testing of the FISH and line as well as the reel component selection.

1.5.3 Mikael Persson – Mechanical Subsystem



Figure 1.7 Mikael Persson

Mikael Persson, a Round 4 Canadian and Swedish SpaceMaster student, is a graduate from McGill University with an Honours degree in Mechanical Engineering, with a focus on mechatronics, multi-body dynamics, and control systems. His previous work has involved the mechanical design and major contributions to software of a Lunar Excavator for NASA's Centennial Challenges for Regolith Excavation within the McGill LunarEx Team. Also, he has worked on unmanned aerial vehicles in designing the sensor system for pose-estimation, along with the sensor fusion algorithms and the 6 degree of freedom control system. This September, Mikael commenced his final year Master studies at the Helsinki University of Technology.

As a member of the Mechanical subsystem, Mikael's contribution to the team involved the mechanical design, construction and testing of the MAIN Payload, including functional and safety elements, the electro-mechanical interfaces, the actuator mechanisms, the reel adaptation and testing.

1.5.4 Mikulas Jandak – Electrical Subsystem (Manager)



Figure 1.8 Mikulas Jandak

Mikulas is a Round 4 SpaceMaster student from the Czech Republic. He holds a bachelors degree in Electrical Engineering and Information Technology, specialising in Cybernetics and Measurement from the Czech Technical University in Prague. Mikulas has much experience in electronics, with experience gained through an summer work in I.J.M. Bohemia a.s. Mikulas commenced his final year of the SpaceMaster programme this October at Cranfield University and is currently working with them and Satellite Services Ltd. on the development of AOCS for

Cubesat applications.

In the reel.SMRT project, Mikulas was responsible for the Electrical Subsystem. He was the designer of the Electronics for the MAIN Payload in the gondola. This included the interfacing between the motors of the reel and line guide as well as the design of sensor systems and power supply system. He was also responsible for constructing and testing his designs.

1.5.5 David Leal Martinez – Electrical Subsystem



Figure 1.9 David Leal Martinez

David Leal Martinez, from Mexico, holds a bachelors degree in electronic systems engineering, which is a mixture of computer science and electronics, and has a Master's degree in Space Science and Technology (SpaceMaster) He did his master thesis on reconfigurable robot societies. David also has experience as a hardware and software designer for new products in the traffic industry in Mexico, and also has led a team to create a city wide Wi-Max based network in the city of Morelia. He has also worked for Focusframe, leading a test automation team in Greenpoint Mortgage (now Capital One Bank) in California, USA.

David is currently working as a Researcher at Helsinki University of Technology working with students developing Ceilbots (<http://autsys.tkk.fi/en/Ceilbot>) and also in Design Factory creating fast prototypes of new Ideas and helping those ideas to become real life products. David is a member of the reel.SMRT Electrical Subsystem. In this role, he is responsible for the electronic design, construction and testing of the FISH payload, including the accelerometers and the rest of the sensor suite.

1.5.6 Jan Speidel – Software Subsystem (Manager)



Figure 1.10 Jan Speidel

Jan Speidel, from Germany, is part of the Round 4 SpaceMaster program and is the software subsystem leader. Jan has completed a Diplom-Ingenieur (FH) Computer Engineering, from the Wolfenbüttel University of Applied Sciences, Germany. As part of his Diplom, he conducted his thesis on the research and Development of a conformal taxi-guidance display for head-up applications. Jan gained software design experience in his internship with DLR, where he was involved in programming of software components for DLR's research simulator. He worked on attitude determination topics in the student project 'AVAO-H' (Aerial Vehicle for Autonomous Helicopter Operation) as well as on 'computer vision' related tasks for an Autonomous Model Airship (AVAO-H).

As part of the reel.SMRT team, Jan was responsible for the software subsystem. Jan is the designer of the software modes and microcontroller programming and

decision cycles. As subsystem manager, in addition to his design tasks, he has written the subsystem requirements, established the task breakdown and performed the risk analysis for his subsystem.

1.5.7 Nawarat Termtanasombat (Waen) - Software Subsystem



Figure 1.11 Waen

Waen has a computer engineering degree with First Class Honours from Chulalongkorn University, Bangkok, Thailand. She has experience both within and leading projects including RoboCup soccer robot, RoboCup rescue robot and designing an automotive driving car including the associated programming. This background has imparted Waen with knowledge of multi-body dynamics and modelling.

Waen began her role in the team as a member of the Mechanical Subsystem, where she was responsible for the simulation of the system. Specifically, modelled the stability of the FISH under a number of drop conditions, to determine the acceleration and position behaviour and the feasibility of the design.

Waen moved to the Software Subsystem following the PDR, where she conducted high level software design, was responsible for the communication protocol and the associated programming of both the microcontrollers and the ground station. She conducted all main programming for the MAIN payload and the FISH including sensor implementation, the control mechanism of the experiment, communication and system integration.

1.5.8 Mark Fittock – Outreach and Science (Formerly)



Figure 1.12 Mark Fittock

Mark Fittock, from Australia, holds a Bachelor of Mechanical Engineering with Honours and a Bachelor of Science majoring in Applied Maths and Astrophysics from Monash University. There, he conducted his engineering thesis on stirling engine design and manufacture. Mark has carried out internships at Volvo Aero as a short term engineer, as a BIO-ENVIRO Innovations Technician and as an EarthTech (Water Department) student engineer. As part of the Round 3 SpaceMaster program, Mark was the leader for his Cansat project. He was also involved in the 2008 BEXUS Program as the Mechanical Engineer of the Stratospheric Census team. He is also the Program Manager and Mechanical Engineer for TREX (Teacup Rocket Experiment).

Mark left the reel.SMRT project following the CDR, to avoid any potential conflicts of interest. During his time in the team, Mark contributed by performing a supporting role for outreach and science. This meant that he worked in tandem

with the Project Manager to organise sponsorship and fundraising for the team, and to design and implement an outreach programme. Being responsible for science meant that Mark researched the scientific background and justification for the mission as well as handling applications and initial team organisation. Since leaving the team, Mark continued in an advisory role and maintained his monetary support to the team according to his original team member contribution

1.5.9 Jürgen Leitner – Software Subsystem (Formerly)



Figure 1.13 Jürgen Leitner

Jürgen Leitner, from Austria, was a member of the software subsystem, but left the team following the CDR due to a high level of commitment and thesis workload that has continued to prevent him from fully contributing to the team.

Jürgen has a Bachelor of Science in Software and Information Engineering from the Technical University of Vienna. As part of his Round 3 SpaceMaster course, Jürgen is currently in Japan for three months conducting his thesis on multi-robot cooperation for space

applications at the Intelligent Space Systems Laboratory of the University of Tokyo.

Jürgen has experience with software and balloon systems, having worked on the reel.E project as part of the HALE program in 2008. He currently holds a ESA YGT position in the Advanced Concepts Team.

Jürgen contributed to the project by designing and updating the webpage and obtaining sponsorship for the reel.SMRT project. He continued to update and maintain the webpage over the duration of the project.

1.6 Funding Support

In order to cover the costs of the reel.SMRT project, many companies were approached regarding sponsorship (see Appendix 6.1) with the sponsorship package and letter as is available in Appendix 6.2.

Above and beyond the student support for the project, ESA Education also has contributed 3000 € to reel.SMRT. As part of the contract between reel.SMRT and ESA Education (see Appendix 6.3), certain tests and criteria must be fulfilled before the BEXUS flight.

Olle Persson of ESRANGE and SSC provided the team with a parachute and parachute deployment system potentially worth well over 1000 €.

Also the reel, line and swivels were provided for free through Daniel Burgess at the Modern Fishing and Modern Boating Magazine, Australia who arranged this



with Daiwa and Platil Fishing Lines. He also acted in an advisory role to the team on the performance of fishing equipment.

Global Communication & Services GmbH (GCS) (25) agreed to sponsor reel.SMRT for 300 €. In return, reel.SMRT promotes GCS in a number of ways, detailed in the sponsorship contract (see Appendix 6.3). Sylvia Meinhart of GCS has also personally contributed 150 € in a particularly kind gesture.

In a similar manner to GCS, RUAG Aerospace Austria GmbH agreed to sponsor reel.SMRT for 800 €, the contract for which can be seen in Appendix 6.3.

Former team Juergen Leitner also pledged 300 € as per the prior team agreement at the time that they were involved. Former team member Mark Fittock pledged to contribute his full team contribution of approximately 800 € to the project.

Six of the team members are enrolled in the Masters level project course for space technology (15 ECTS) at IRV. Funding and support is linked to the successful completion of objectives within this subject above and beyond the requirements of BEXUS. The funding available is 5000 SEK for expenditure on products that must be ordered from Swedish companies. Testing facilities and other materials were kindly made available upon request and availability. LTU has also offered the team an additional 5000 SEK to assist in covering the budget, and this is currently under discussion at the time of writing. In return for this funding, the team would donate to LTU the goods purchased with ESA and LTU sponsorship, in addition to other goods of no resell value.

Prof. Reinhard Gerndt, of Wolfenbüttel University of Applied Sciences has kindly provided gyroscopes for use on the reel.SMRT payload. These are to be returned in the event that they are in working order upon retrieval of the payload (see agreement in Appendix 6.3).

A significant component of the funding comes from the students themselves. Due to the high costs of the project the entire budget has not been covered by sponsors. Ideally, all members of the team should contribute equally independent of work levels. The amount to be contributed currently is set to 800 €, which is much more than the original 300 € anticipated. This is largely a consequence of an extensive testing phase that required design iterations and replacement of some broken components. For more details of the budget please see Appendix 2.1.



2 MISSION REQUIREMENTS

This chapter includes the definition of all requirements to achieve the mission objectives of the reel.SMRT Project. Mission Level and Subsystem Level requirements are presented and justified. Within these categories, the functional, technical and operational requirements are listed. The functional requirements define how well the system must perform to meet its objectives, whilst the technical requirements determine how the system operates (26). Operational requirements involve qualitative and quantitative parameters that specify the desired capabilities of the system and serve as a basis for determining the operational effectiveness and suitability of the system prior to launch. These operational requirements drive the functional requirements (26). This mission is constrained primarily by the BEXUS User Manual (27) requirements and safety requirements as dictated by ESA and EuroLaunch. Sources from which the requirements were derived include the scientific parameters relating to the mission profile. The requirements are written so as to neither dictate nor impose needless constraints on design, but rather specify what is necessary to perform a successful mission as well as operate the system (26). Each requirement is numbered such that it can be tracked and referred to throughout the design process.

Within these boundaries, the Primary and Secondary Objectives shall be achieved. It is from these high-level system requirements that the subsystem level requirements are derived. The high level (mission level) requirements and their derivations are expressed in Section 2.1. Sections 2.2 to 2.4 describe the requirements for each subsystem.

Each requirement was addressed by the design, with a series of verification tests performed with the aim of ensuring mission success. Appendix 1.2 includes a requirement verification table, detailing the requirements verification process and its current status. This includes a test or verification activity for each requirement, such that once all the requirements are met the mission objectives may be achieved.

The experiment was ultimately fully functionally tested and was lifted by the balloon in this condition. This is with the exception of the high data rate transmission to the ground (there was software version error), which meant the dropped acceleration data was only stored on the FISH, rather than being transmitted to the ground station. All performances were verified during integration as working and this was repeated by test at short access before launch.



2.1 Mission Level Requirements

2.1.1 Mission Level Functional Requirements

The reel.SMRT system shall:

- Req.F.1 Achieve an acceleration performance of the FISH to a gravity of less than $10^{-3}g$ for at least 2 seconds, in the x, y and z directions.
Response to Obj.P.1. This acceleration value is similar to the performance of zero-G flights.
- Req.F.2 Drop a payload to a distance of at least 50 m, return it to the gondola and repeat this action.
Response to Obj.P.1.
- Req.F.3 Lower a payload to a distance of at least 50 m and return it to the gondola, and repeat this action.
Response to Obj.P.2.
- Req.F.4 Supply the ground station with periodic feedback sensor data for analysis at the ground station.
- Req.F.5 Have a total weight of no more than 25 kg.
- Req.F.6 Have a total volume of no more than 0.2 m^3 .
- Req.F.7 Survive atmospheric temperature (possibly 226 K) for the mission duration.
- Req.F.8 Receive commands from and transmit to the ground station.
- Req.F.9 Investigate the feasibility of the system as a reduced gravity environment platform for drops of longer duration.
- Req.F.10 Assess the drift of the FISH during a drop and its consequences on the whole system and the measurement accuracy.
- Req.F.11 Realise an outreach program.
In accordance with the Terms and Conditions of the BEXUS Program.

The reel.SMRT system should:

- Req.F.12 Achieve an acceleration performance of the FISH to a gravity of less than $10^{-6}g$ for at least 2 seconds, in the x, y and z directions.
Response to Obj.P.1: $10^{-6}g$ is the performance of drop towers.
- Req.F.13 Have a total weight of no more than 25 kg.



2.1.2 Mission Level Technical Requirements

The reel.SMRT system shall:

- Req.T.1 Implement a reel-based mechanism.
- Req.T.2 Provide an intrinsic power source within the FISH and the MAIN Payload.
In accordance with BEXUS Manual (27) power supply capacity.

2.1.3 Mission Level Operational Requirements

The reel.SMRT system shall:

- Req.O.1 Determine the acceleration performance of the FISH to an accuracy of at least $10^{-3}g$ in the x, y and z directions.
To determine Req.F.1
- Req.O.2 Involve no unmitigated risks with a risk analysis value greater than 15.
- Req.O.3 Implement a parachute within the FISH as a safety mechanism.
To achieve Req.O.2
- Req.O.4 Implement a reel-based mechanism to lower and raise the FISH.
To achieve Req.F.3
- Req.O.5 Communicate between the FISH and MAIN Payload.
- Req.O.6 Implement a drop-on-command ability for the FISH.
- Req.O.7 Operate for the expected lifetime of five hours mission duration.
- Req.O.8 Shall ensure compliance with the requirements of the BEXUS User Manual.
In accordance with the Terms and Conditions of the BEXUS Programme.
- Req.O.9 Comply with the overall project schedule and any requests made by ESA, SNSB or EuroLaunch in relation to the execution of the project.
In accordance with the Terms and Conditions of the BEXUS Programme.
- Req.O.10 Inform EuroLaunch immediately in the case of a problem in the experiment that may affect its performance, impact the schedule or have safety implications.
In accordance with the Terms and Conditions of the BEXUS Programme.
- Req.O.11 Not exceed the maximum project budget of 4000 EUR beyond external funding.
Determined by the financial limitations of team members.



The reel.SMRT system should:

- Req.O.12 Determine the acceleration performance of the FISH to an accuracy of $10^{-6}g$ in the x, y and z directions.
To determine Req.F.12

2.2 Mechanical Subsystem Requirements

2.2.1 Mechanical Subsystem Functional Requirements

The reel.SMRT Mechanical Subsystem shall:

- Req.F.M.1 Release the FISH into free-fall.
Response to Req.F.1 and Req.F.2
- Req.F.M.2 Safely bring the FISH to a halt.
Response to Req.F.2
- Req.F.M.3 Recover the payload to the initial state in preparation for another drop.
Response to Req.F.2
- Req.F.M.4 Simulate the aerodynamics stability of the FISH.
Response to Req.F.9
- Req.F.M.5 Predict the level of friction in the line system.
Response to Req.F.9
- Req.F.M.6 Simulate the position of the FISH.
Response to Req.F.9
- Req.F.M.7 Limit the mass of the FISH to 2 kg.
Response to Req.F.5
- Req.F.M.8 Limit the mass of the MAIN Payload to 23.5 kg.
Response to Req.F.5.
- Req.F.M.9 Have vertical FISH dimension of no more than 0.85 m.
Response to Req.F.6.
- Req.F.M.10 Impart shock forces of no more than 200 N magnitude transferable through the gondola.
Response to Req.O.2 and Req.O.8
- Req.F.M.11 Design the FISH to be dynamically stable.
Response to Req.F.1.

2.2.2 Mechanical Subsystem Technical Requirements

The reel.SMRT Mechanical Subsystem shall:

- Req.T.M.1 Protect the payload from mission physics and thermal hazards
Response to Req.O.2, Req.O.7 and Req.F.M.1
- Req.T.M.2 Be able to reduce the velocity of the drop payload to a safe value for all mission scenarios.



The reel.SMRT Mechanical Subsystem should:

2.2.3 Mechanical Subsystem Operational Requirements

Req.O.M.1 Include the drop payload in the total volume.
Response to Req.F.7.

Req.O.M.2 Minimise aerodynamic drag on the payload.
Response to Obj.P.1 and Req.F.1

Req.O.M.4 Maintain the stability of the FISH on all six degrees of freedom.
Response to Obj.P.1, Req.F.1 and Req.O.2.



2.1 Electrical Subsystem Requirements

2.1.1 Electrical Subsystem Functional Requirements

The reel.SMRT Electrical Subsystem shall:

- Req.F.E.1 Implement Analogue to Digital converters capable of providing resolution below noise level of both accelerometers and gyroscopes in both the FISH and the MAIN Payload.
Response to Req.F.12
- Req.F.E.2 Measure acceleration without insignificant delay with respect to the time of the drop.
Response to Req.F.12
- Req.F.E.3 Implement ADC capable of providing numerous samples of acceleration and rotation in both FISH and the MAIN Payload.
Response to Req.F.4
- Req.F.E.4 Be capable of being provided with status data of the FISH during the entire drop.
Response to Req.F.4

The reel.SMRT Electrical Subsystem should:

- Req.F.E.5 Implement ground station, which is to be provided with status data of both FISH and the MAIN Payload.
Response to Req.F.4
- Req.F.E.6 Implement external memory, which should be easy to remove from the MAIN Payload and the FISH.
- Req.F.E.7 Be capable of monitoring the position of the FISH in the lower and upper part of the MAIN Payload.
Response to Req.F.4
- Req.F.E.8 Determine the relative position between inertial sensors of the MAIN Payload and the FISH.
Response to Req.F.9
- Req.F.E.9 Be capable of synchronizing the acquisition systems on the FISH and on the MAIN Payload.
Response to Req.F.9
- Req.F.E.10 Implement microcontroller capable of controlling motors.
Response to Req.F.2
- Req.F.E.11 The operation status of the main motor shall be monitored.
Response to Req.F.4
- Req.F.E.12 Be able to monitor the battery status.
Response to Req.F.4
- Req.F.E.13 Implement separated acquisition system and the power electronic.



- Req.F.E.14 Monitor the position of the bail.
Response to Req.F.4
- Req.F.E.15 Implement microcontroller capable of monitoring the status of the FISH, status of the motors and position of the bail in real time.
Response to Req.F.4
- Reg. F.E.16 Be turned on and off by user and the current power status should be visible.

2.1.2 Electrical Subsystem Technical Requirements

The reel.SMRT Electrical Subsystem shall:

- Req.T.E.1 Implement AD Converter on the fish and the MAIN Payload capable of sampling the acceleration in x, y and z axis at the data rate of more or equal 100 samples per second.
Response to Req.F.E.3
- Req.T.E.2 Implement AD Converter on the fish and MAIN Payload with resolution of more or equal 16 bits.
Response to Req.F.E.1
- Req.T.E.3 Measure the acceleration of less than 10 mg.
Response Req.F.1
- Req.T.E.4 Implement accelerometer with the bandwidth of more than 100 Hz.
Response to Req.F.E.2
- Req.T.E.6 Implement the communication capable of communicating in the range of more than 70m.
Response to Req.F.E.4
- Req.T.E.7 Implement the external memory on both fish and the MAIN Payload to be bigger than 64 MB.
Response to Req.F.S.2

The reel.SMRT Electrical Subsystem should:

- Req.T.E.8 Implement switch for turning on and off the both MAIN Payload and the fish.
Response to Reg. F.E.16
- Req.T.E.9 Be equipped with LED to indicate on/off status and the status of the communication between the FISH and MAIN Payload.
Response to Reg. F.E.16



2.1.3 Electrical Subsystem Operational Requirements

The reel.SMART Electrical Subsystem shall:

- Req.O.E.1 Implement battery on the MAIN Payload capable of providing energy for at least 20 drops and for the operational time of 5 hours
Response to Req.O.7
- Req.O.E.2 Implement sensor package having redundancy to reduce single point of failure
Response to Req.O.2
- Req.O.E.3 Implement battery pack capable of providing the motors with sufficient current
Response to Req.O.7
- Req.O.E.4 Implement battery pack capable of fulfilling safety requirements
Response to Req.O.8
- Req.O.E.6 Implement motor capable of operating in the thin atmosphere.
Response to Req.O.4
- Req.O.E.7 Implement a sensor package in the FISH able to provide acceleration data for the x, y and z direction in the order of milligravity, with noise on the order of microgravity.
- Req.O.E.7 Calibrate accelerometers in order to be able to measure acceleration of the order of a minimum of 10mg.
Response to Req.O.1

2.2 Software Subsystem Requirements

2.2.1 Software Subsystem Functional Requirements

The reel.SMART Software Subsystem shall:

- Req.F.S.1 Control the experiment.
The experiment shall be controlled from the ground during the entire mission. Drops shall only be executed in accordance with the balloon control team.
- Req.F.S.2 Store sensor data during flight for post-processing
The sensor data shall be analysed post-flight to demonstrate the low gravity performance of the system.
- Req.F.S.3 Guarantee emergency procedures in case of mechanical or electrical failure.
Response to requirement Req.O.7; the FISH must not pose a threat to people on the ground or the other balloon payloads.



The reel.SMRT Software Subsystem should:

- Req.F.S.4 Allow uplink and downlink capability to monitor the experiment during the mission.
A ground station to experiment link provides the ability to react to unforeseen flight behaviour, or drop-on-command as desired.

2.2.2 Software Subsystem Technical Requirements

- Req.T.S.1 The reel.SMRT Software subsystem should be based on a real-time operating system (RTOS).
Many tasks during the experiment are highly time critical. A RTOS ensures a maximum execution time for each task.
- Req.T.S.2 Adhere to the allocations received in the team budgets.

2.2.3 Software Subsystem Operational Requirements

The reel.SMRT Software Subsystem shall:

- Req.O.S.1 Control the actuators and motors during the flight.
At absolute minimum, one slow reel and one free-fall experiment shall be conducted.
- Req.O.S.2 Detect software faults and recover from them using watchdog and Power-on-reset functionality.
The Watchdog detects hang-ups of the programme and restarts the microcontroller if necessary, enabling the system to recover from the malfunction.

The reel.SMRT Software Subsystem should:

- Req.O.S.3 Maintain operation of FISH even if FISH-payload communication is lost.
The mission objective can still be achieved even if the communication link fails, if the FISH is recovered such that data can be extracted.

3 EXPERIMENT DESCRIPTION

In this chapter the experiment is presented with justifications. The chapter commences with an experiment overview, with a summary of key components and budgets for mass, volume, power and data. The interfaces between subsystems and to the gondola are then defined, with distinct responsibilities established. Finally, the design for each individual subsystem is expounded upon and evaluated.

3.1 Experiment Overview

To achieve the objectives, the reel.SMRT system design consists of three primary segments: a ground station, the MAIN Payload and the dropped payload, which is known as the 'Free-falling Instrument System Housing' or FISH. Each of these segments is electrically independent. A system diagram comprised of these segments is shown in Figure 3.1.

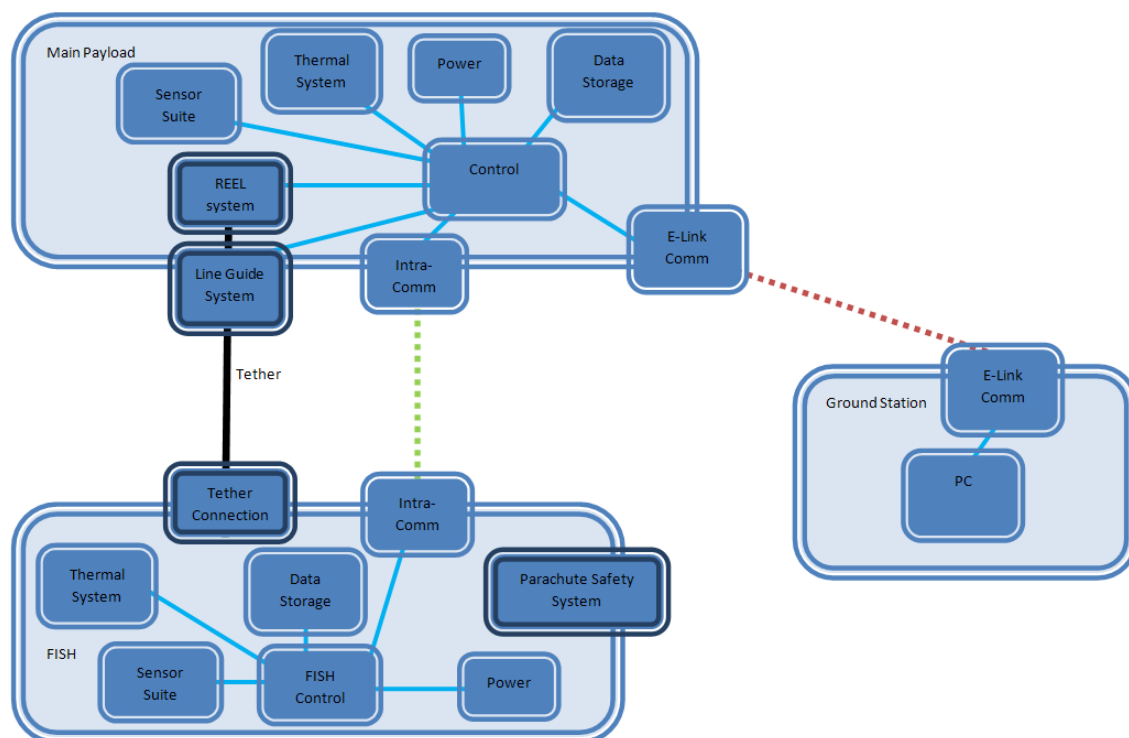


Figure 3.1 reel.SMRT system diagram

The MAIN Payload is nested in the balloon gondola and consists of the REEL system, line guide system, sensor suite, thermal system, power unit, intra-communication link and data storage. There is also the E-Link communication to the ground for uplink of command and downlink of housekeeping data. The REEL system forms the mechanical interface with the FISH. It consists of a reel, motors, servo motors and a line guide. The line guide system is a safety system that can

operate independently to the MAIN Payload, it consists of a line guide and motor for reeling the FISH back to the MAIN Payload and also has a safety brake which will lock the line in the case of power failure.

The process of dropping the FISH and reeling it up again is called a CATCH. The intra communication between the FISH and the MAIN Payload is called a SMRT KISS. A SMRT KISS takes place for the duration of each CATCH, with the data from the FISH being both stored within it and transferred to the MAIN Payload via short range radio modules for back up storage and then downlink. The FISH is a 1.6kg vessel with its own power, thermal system, data storage, sensor suite and parachute. The controller used both on the MAIN Payload and FISH is the same component. An approximated system representation is depicted in Figure 3.2.

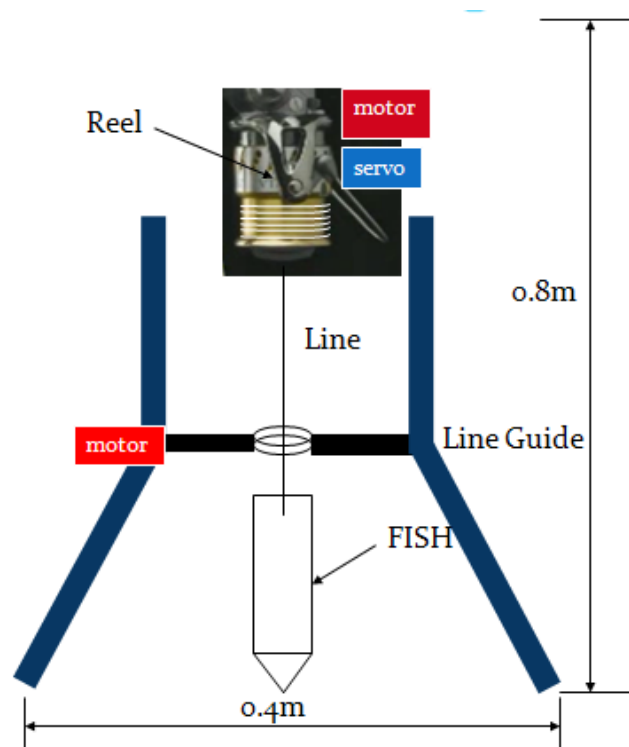


Figure 3.2 Simplified System Representation

Therefore, the primary components necessary to support and fulfil the objectives and requirements of the mission are:

- IR Sensors
- Hall Sensors
- Incremental Encoders
- Temperature Sensors
- Accelerometers
- Gyroscopes



- Communication Modules
- Reel
- Braking System
- High Strength Line
- Safety System: parachute, line guide, CYPRES unit (parachute deployment mechanism)
- Motors
- Sensors to measure acceleration and position of the FISH for sufficient accuracy matching to the requirements
- Communications hardware between the FISH and the MAIN Payload on the gondola, between the MAIN Payload and the gondola and between the gondola and the ground station
- Control System
- Data Storage
- Power Supply
- Thermal System

3.2 Modes

The system has been designed to have a free-fall distance of 50m, and a total reel distance of 70m: large enough to obtain relevant data for the feasibility investigation and small enough to simplify the design to enable use of off-the-shelf components. The reel.SMRT system shall test two modes to achieve the objectives of the mission: a 'Drop Mode' that aims to produce minimal gravity conditions, and a 'Slow Reel Mode', for tethered applications such as data sampling over a height range or tethered experiments. The reel up time for each drop is approximately two minutes. The number of samples during each mode is 1000 per second for each sensor due to the high accuracy required over the short time of the drop. The time between each drop and slow reel modes shall be a minimum of two minutes for data transfer, and may be longer if required or the motors are determined to be overheating (Temperature is continuously measured by a thermometer attached to the microcontroller of the MAIN Payload).

3.2.1 Drop Mode

The Drop Mode has three phases: free-fall phase, deceleration phase and recovery phase. These phases are depicted in Figure 3.3. In the free-fall phase, the FISH begins inside the MAIN Payload. The line guide is then unlocked and the bail mechanism is released, enabling the FISH to fall under gravity as the line spools off the reel. Once 50m is reached, which is determined by the length of time that has passed, the bail mechanism shall be shut by turning the motor on the reel handle and forcing it past the bail close mechanism. All calculations have taken into account the force of gravity acting on the FISH during all phases of the mission. This ends the free-fall phase. In the deceleration phase, the brake is applied automatically by the bail closing and the FISH is decelerated to a halt over approximately 20 m. Then,

the recovery phase begins. In the recovery phase, the FISH will be reeled up back into the MAIN Payload to complete the CATCH. If necessary, the line locking mechanism may be applied between CATCHs, by spinning the line guide using a motor to create a friction lock.

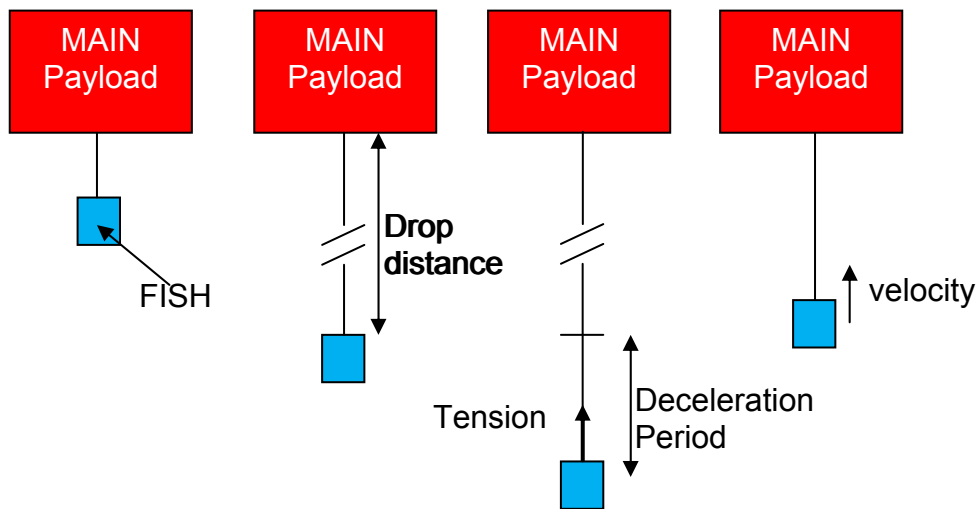


Figure 3.3 Drop Mode (where the shortest stopping distance expected is 11m, incurring a 5g deceleration)

Figure 3.4 displays the decision tree for the drop mode. During the drop the behaviour of all relevant feedback sensors is monitored. If any malfunction occurs the emergency recovery mode is activated. This mode helps to bring the experiment into a safe state to allow the recovery of the experiment.

Drop mode

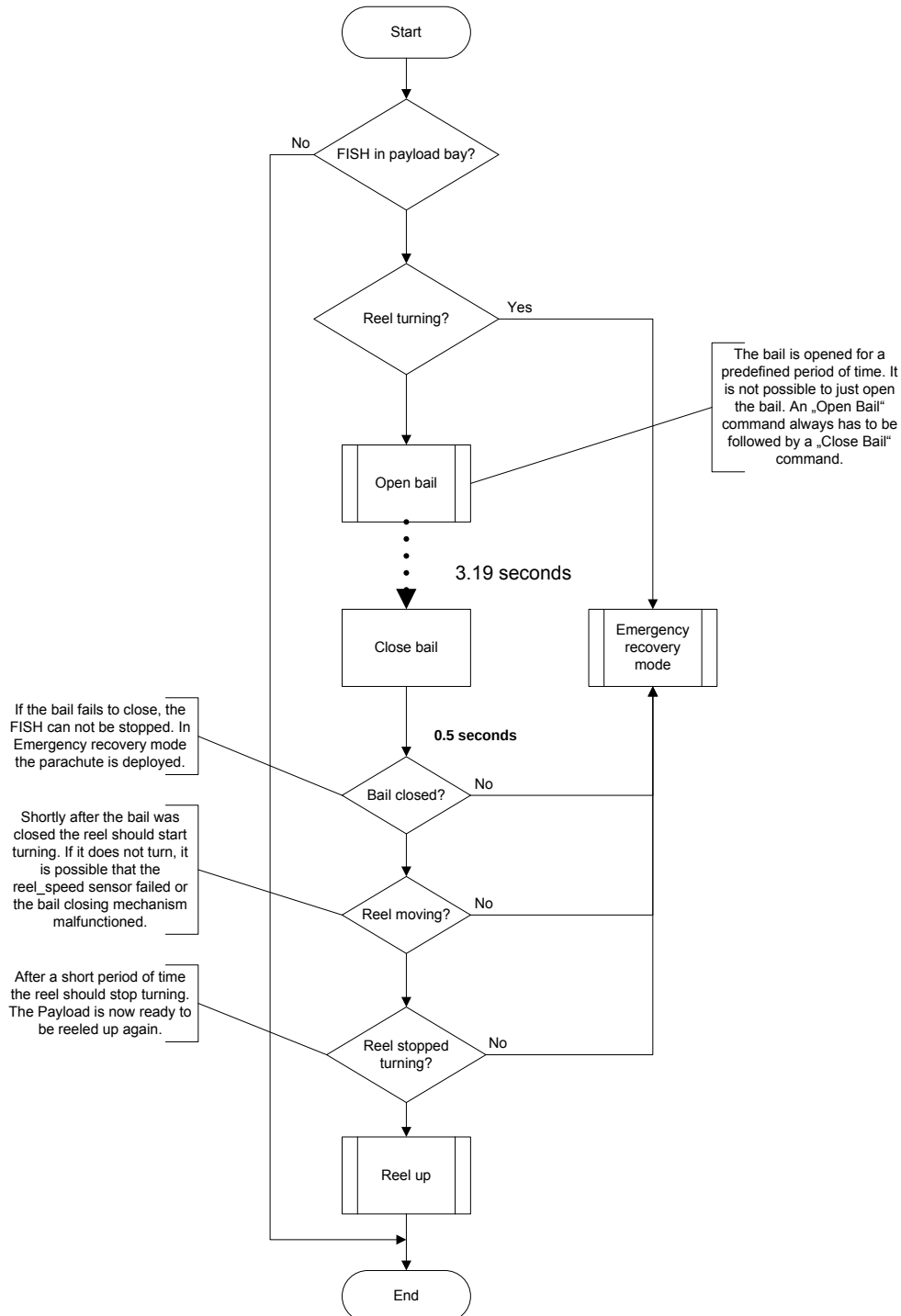


Figure 3.4 Drop Mode Diagram

3.2.2 Slow Reel Mode

The Slow Reel Mode is similar to the Drop Mode but with the free-fall phase replaced by the reel-down phase. The Slow Reel Mode is depicted in Figure 3.5. In the reel-down phase the bail mechanism remains closed. The FISH is then lowered by using the motor to reel down the line by rotating the handle forward. In this way, the speed of the reeling and the tension in the line may be varied as applicable for the application. The distance of the FISH from the gondola, in the slow reel mode, is limited only by the length of the line. By lowering the FISH a further distance, information may be obtained about the perturbation effects and stability of the FISH on the end of the long tether.

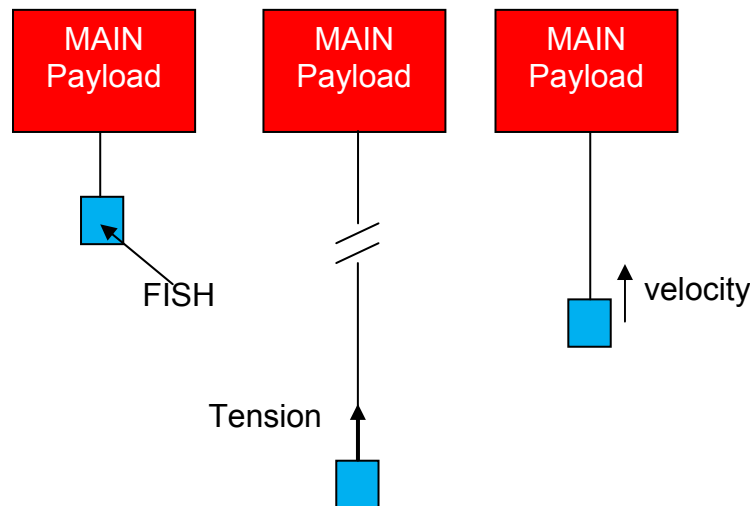


Figure 3.5 Slow Reel Mode.

Figure 3.6 shows the decision tree of the slow reel mode. Again, during the reeling process the relevant sensors are monitored carefully. In case of a sensor malfunction, the system enters the emergency recovery mode to reach a predefined state and to allow a safe recovery of the FISH without posing a threat to life on the ground.

Slow reel mode

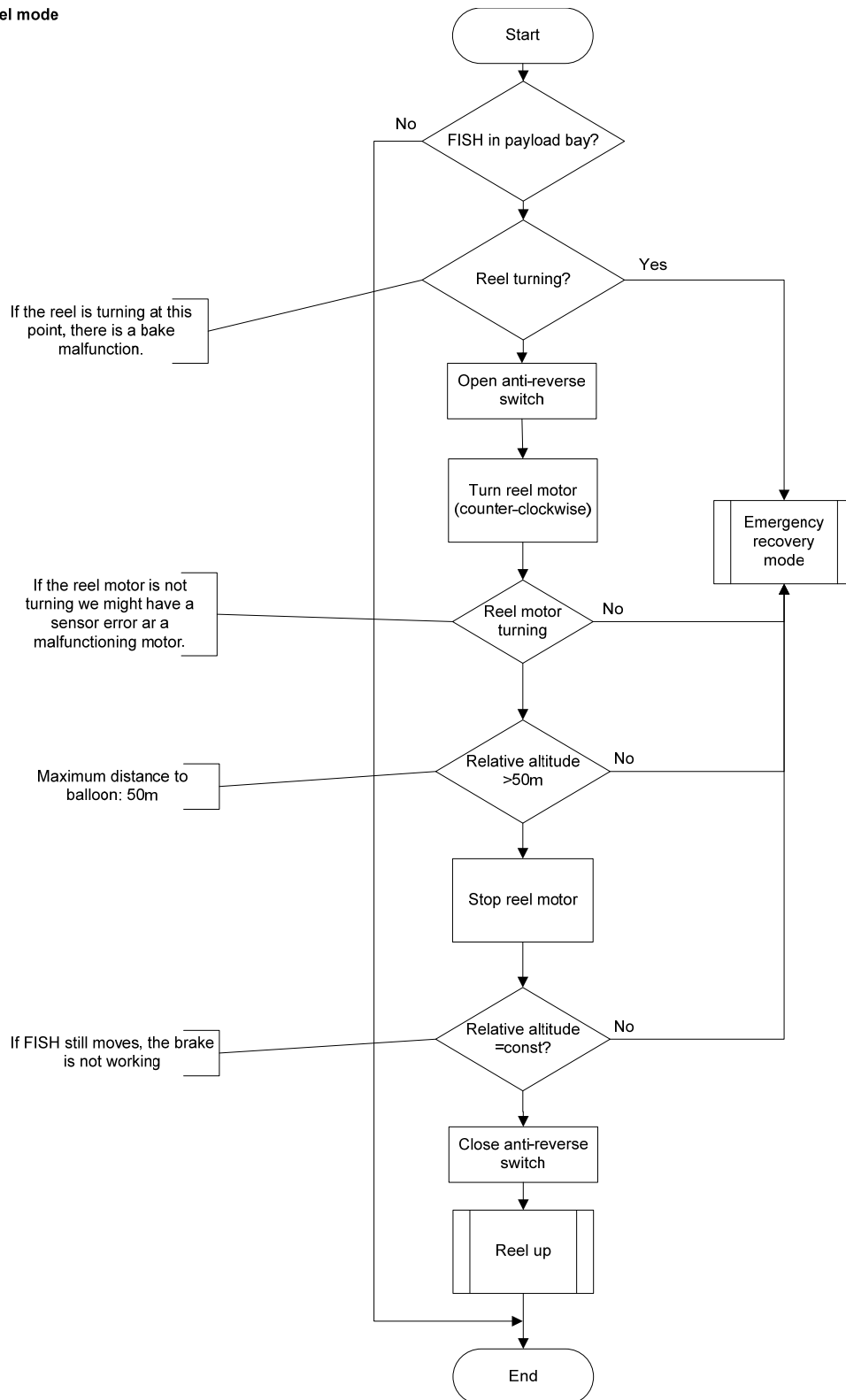


Figure 3.6 Slow Reel Mode Diagram



3.3 Mission Operations

3.3.1 Sequence

3.3.1.1 Power-Safe Mode

Before the launch, the reel.SMRT experiment is set to power-safe mode. When in this mode, almost all active components of the experiment are switched off. Only one temperature sensor is still powered. These sensors are needed to monitor the active heating of the electronics bay on the MAIN Payload. During the power-safe mode, the communication links from the ground to the MAIN Payload and further to the FISH are fully functioning. This allows the operator on the ground to perform tests or even start to work on contingencies if malfunctions are already noticeable in this early stage of the flight.

3.3.1.2 Checkout of All Sensors

As soon as the free-float segment of the balloon flight is reached (detected by a decrease of vertical speed from the GPS on the MAIN Payload) the experiment, including all sensors, is powered up automatically (a manual power-up sequence can be executed from the ground as well if necessary). A test packet is transmitted to the ground station with values from all sensors on board to find out if they all work properly. If not, an alternate procedure can be activated from the ground.

3.3.1.3 Checkout of Actuators

Next, all actuators are checked out. The FISH will be reeled down until it has left the payload bay completely. Allowing the testing of the proximity sensors' performance inside the payload bay that detect the position of the FISH when reeled up into the MAIN Payload.

3.3.1.4 Test Reel Up Sequence

In this sequence, the FISH shall be reeled up again to check if the reel up algorithm works as expected. The reel up sequence shall be stopped according to the proximity sensor data inside the MAIN Payload.

At this point all necessary checkouts are accomplished. The reel.SMRT is now ready for the first slow reel.

3.3.1.5 First Slow Reel Mode

The first slow reel will be the slowest one of the flight. Its purpose is to test the performance of the motors (thermal aspect) and the feedback sensors both from the reel and the reel motor. If a sensor is not working properly another sensor may be used and the experiment can be executed as planned.

If the performance of the experiment (especially the motor) is as expected, the slow reel up can be executed. During the way up, the reeling process will be stopped to demonstrate the ability to take sensor values at different altitudes. As soon as the



FISH is back in the payload bay the data transfer performance can be analyzed in aspect of average data rate and maximum transfer range.

In the case all tests are passed to this point, the first drop mode test shall be executed.

3.3.1.6 First drop mode

If all sensors and actuators are working as expected, the drop can be initiated. This drop will be a regular one of approximately two seconds duration. At the end of each CATCH, the temperature of the reel motor is verified. If the motor temperature is too high, the next drop will be delayed.

3.3.1.7 Further Drops

The sequence of the experiments can be chosen freely, constrained only by the Safety Officer at ESRANGE. The drops can be repeated as often as necessary. However, the limiting factors are the duration of the balloon in free-float, the temperature of the reel motor, the degradation of the brake and the size of the memory storage.

3.3.1.8 Pre-Descent System Lockdown

Before the gondola is cut off from the balloon the FISH shall be reeled up and stowed in the payload bay. The FISH is then locked in the bay using the line guide and motor and the line guide safety brake will be applied.

3.3.1.9 Descent

As soon as the accelerometers detect a high sink rate over an extended period of time, the reel.SMRT experiment is put into power-safe mode again with only the essential sensors still being powered on. After impact detection, the experiment shuts itself down completely in order to minimise the risk of short circuits in case the gondola lands on a wet surface.

3.3.2 Tether Break Scenario

If during the experiments the tether should fail, this will be detected by the CYPRES system, which will deploy the parachute decreasing the fall rate so that the FISH does not pose a threat to life or property.

3.3.3 Power-On-Reset

In case of a temporary power loss or if a microcontroller has to restart, the Power-On-Reset function is executed first to bring the experiment into a safe state, independently from the time that the reset occurred even during a drop. With this function, it is possible to recover the experiment at any time without risking the mission or safety. The diagram showing the power on reset procedure is shown in Figure 3.7.

Power-On-Reset (POR)

(This sequence is executed after startup and if a controller reset (initiated by the watchdog) is executed)

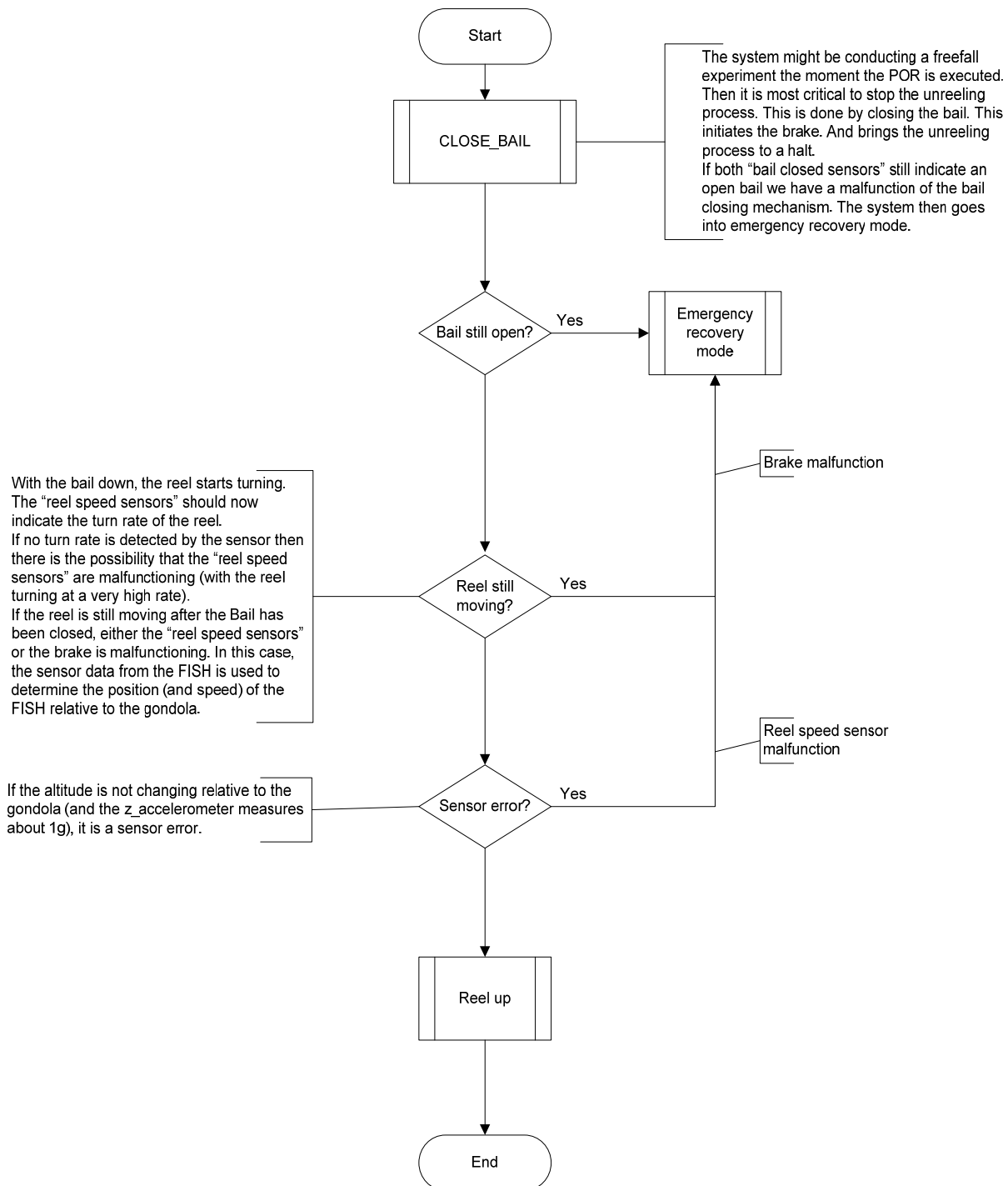


Figure 3.7 Power-On-Reset Diagram

3.3.4 Component List

The main components are summarised in Table 3.1. An in-depth Component list is situated in Appendix 1.1.

Components	Material	Source	Description
Mechanical Subsystem			
MAIN Payload			
Universal Profiles PU25	Al. 6061	Solectro PU25	Aluminum profile extrusions
Line Guide	Al. 6061	Custom Machined	Fork which is powered and enables emergency braking and reeling
Daiwa Saltiga Surf Spinning Reel 6000	Mg Alloy	Daiwa	Dual full time infinite anti reverse Machined Aluminium spool Air metal magnesium body treated for saltwater use
Reel Motor	Various	Maxon 251601 203119	EC 45 flat Ø45 mm, brushless, 50 Watt, with Hall sensors Planetary Gearhead GP 42 C Ø42 mm, 3 - 15 Nm, Ceramic Version
Line Guide Motor	Various	Maxon 251601 203119	EC 45 flat Ø45 mm, brushless, 50 Watt, with Hall sensors Planetary Gearhead GP 42 C Ø42 mm, 3 - 15 Nm, Ceramic Version
Servo Motor	Various	Robotis RX-64	Robotis Dynamixel RX-64, 12V serial network servo, 64 kg-cm holding torque
Linear Actuator	Various	Firgelli L12-30-210-12-P	40 N, 30 mm, 12 V, Analog
Safety Brake	Various	OguraRNB-0.8G	8 Nm, 30mm thick, 97mm diam., power-off brake, 24V, 15W
FISH			
Parachute		ESRANGE	370g, 70mm diameter, storage size 50mm x 150 mm diameter
Dyneema Braided Line	Dyneema	Platypus	200m, 200N force
CYPRES Unit		CYPRES	COTS, will release parachute at certain activation parameters
Swivel	Steel	Daiwa	High Strength Swivel
Electrical Subsystem			
ASC 5421	-	ASC Gmbh	High precision accelerometer pack
ADR445 B grade	-	Farnell	Precise 5 V reference
LIS3L02AQ3	-	Farnell	Linear accelerometer
xBee Pro 868	-	Farnell	-
IP Camera	varios	LevelOne,FCS-1030	-
LS 14250	-	Saft	3.6 V Primary Li-SOCL ₂ Battery
ADXR150	-	-	Gyros
LP38691DT-5.0	-	Farnell	5V Regulator
LP38691DT-3.3	-	Farnell	3.3 V Regulator

LP38691DT-1.8	-	Farnell	1.8 V Regulator
LPC2364	-	Farnell	ARM 7 Micro controller
Molex 49225-0821	-	Farnell	microSD memory mount
Sandisk microSD 2GB	-	Verkkokaupa	2GB microSD memory card
Capacitors, Resistors and Crystals	-	Farnell	Electronic components needed by the main components
ADC1278	-	Farnell	Precise Analogue - Digital converter

Table 2 Summarised Component List

3.3.5 Mass Budget

The mass budget has been summarised in Table 3. These are the main constraining masses of the system, which take into account all components necessary to construct the system. A detailed budget listing these components is displayed in Appendix 5.1.

- The total mass of the experiment is 26kg with the FISH at 1.6kg.

Selected Component	Qty	Mass per Item (g)	Mass total (g)	Confidence (%)
MAIN Payload			24,000	
Daiwa Saltiga Surf Spinning reel	1	530	530	100
Reel Motor	1	500	500	100
Line Guide Motor	1	500	500	100
FISH			1,600	
Skin	1	322.1	322.1	100
Parachute	1	385	385	100
CYPRES Unit	1	350.8	350.8	100
Structure		517	517	100
Batteries	4	8.5	51	90
Line			220	
Dyneema Braided Line	1	200	200	80
Swivel	1	10	20	70
Total (g)			25,820	

Table 3 Summarised Mass Budget of the System

3.3.6 Volume Budget

The volume budget is summarised in Table 4 for the key design constraining components of the reel.SMRT system.

Component	x (mm)	y (mm)	z (mm)	Volume (mm ³)
MAIN Payload	500	500	900	225,000,000
Reel	100	110	80	880,000
Reel Motor	60	60	76	273,600
Line Guide Motor	60	60	76	273,600
Line Guide	14	40	120	35,059
Servos	40.6	19.8	37.8	30,387
Battery	106	46	35	170,660
FISH	D 150		275	4,859,651
Batteries	D 14.5		24.5	16,182
Parachute	D 150		50	883,573
Electronics	55	60	50	135,000
CYPRES Unit	82	55	29	133,168
Accelerometer	16	18	23.6	6,797

Table 4 Volume Budget of Important Components

Overall the MAIN Payload will be 0.4x0.4x0.8 m, with a combined volume of 0.128 m³. The FISH will be housed in the MAIN Payload thus it will require any more volume in the Gondola.

3.3.7 Data Budget

The critical components concerning the data budget are:

- The mass memory (SD-Card) on the FISH
- The mass memory (SD-Card) on the MAIN Payload
- The communication link between Fish and MAIN Payload (xBee Pro 868)
- The communication link between MAIN Payload and ground station (Ethernet/E-Link)

During reeling experiments a large amount of sensor data is collected at a high rate. Therefore the peak data rate will occur during the slow reel mode or free fall mode and shortly after that. Table 5 shows the bit rates of each set of sensors and the total data rate that can occur during reeling on the MAIN Payload as well as on the FISH.

Component	No.	Sampling time [1/s]	Resolution [Bit]	Data Budget [kBit/s]
MAIN Payload				113.34
Accelerometers	4	1000	16	64.0
Gyroscopes	3	1000	16	48.0
Temperature sensors	5	1	16	0.08
Proximity sensors	3	20	1	0.06
Hall sensors	3	20	10	0.6
Reel velocity sensors	4	100	1	0.4
Current measurement sensor	1	20	10	0.2
FISH				180.616
Accelerometers (high precision, low bandwidth)	3	1000	24	72.0
Accelerometers (low precision, high bandwidth)	3	1000	12	36.0
Gyroscopes	3	1000	24	72.0
Temperature sensors	9	1	24	0.216
Reel velocity sensors	4	100	1	0.4

Table 5 Data Budget

The data budget is designed for a maximum of 20 freefall experiments during flight each lasting approximately 10 seconds during the drop. During that time the amount of data generated is:

$$20 \cdot 10s \cdot \left(113.34 \frac{kBit}{s} + 180.616 \frac{kBit}{s} \right) = 58.7912 MBit$$

When no experiments are executed and the balloon is in the free float phase and slow reel mode the sensors still collect data but at a much lower rate (about 100 times less). This reduces the total data budget of the flight significantly. With an expected free float time of up to three hours, the maximum amount of data generated is:

$$3 \cdot 60 \cdot 60 \cdot \left(113.34 \frac{kBit}{s} + 180.616 \frac{kBit}{s} \right) \cdot \frac{1}{100} = 31.747248 MBit$$



This gives the results in a total of 90.58 Mbit of sensor data generated during the entire flight.

All sensor data generated on board the FISH will be stored on the local SD-Card and transmitted to the MAIN Payload at the same time. On the SD-Card, which is located on the MAIN Payload both the sensor data received from the FISH as well as the locally collected data will be stored. That amount is:

$$\frac{58.7912\text{MBit}}{8} = 7.3489\text{MByte} \quad \text{on the FISH and}$$

$$\frac{31.763448\text{MBit}}{8} + 7.35489\text{MByte} = 11.32\text{MByte}$$

This amount of data is stored on the memory cards on board the FISH and the MAIN Payload.

3.3.8 Power Budget

The Power Budget is shown in Table 3.5 for the FISH. More details may be found in Appendix 3.

Unit	Current Consumption (mA)	At voltage (V)	Power (mW)	Power dissipation (mW)	Units	sum (mW)
Microprocesor	125	3.3	412.5	1500	1	412.5
Colibry M8002.D	0.4	5	2	0	3	6
ADS1274	50	5	250	285	1	250
ADS1274	18	3.3	59.4	0	1	59.4
ADS1274	0.15	1.8	0.27	0	1	0.27
HMC6352	1	3.3	3.3	0	1	3.3
LIS3L02AQ3	0.85	3.3	2.805	0	1	2.805
Xbee	45	3.3	148.5	0	1	148.5
Total						882.775

Table 6 Power Budget of the FISH

The calculation showed that if the capacity of the batteries in low temperature is only 60% of the capacity stated, the system will operate for 7.5 hours. This is valid for 3 packs connected in parallel, so in case of one battery pack failure the system will still be able to operate for 3.75 hours which is 75% of the total operation time.

System sensors						
	#	Voltage [V]	Current [mA]	Power[mW]	Time[%]	Equivalent [mW]
LPC2368	1	3.3	100	330	100	330
IMU Unit	1	5	150	750	100	750
SHARP GP2D120XJ00F	3	5	80	1200	100	1200
OPA735AIDBVT	1	3.3	0.75	2.475	100	2.475
A3213EUA-T	4	3.3	2	26.4	100	26.4
SD card	1	3.3	80	264	100	264
ZigBee	1	3.3	50	165	100	165
HEDS-9730, encoder	2	3.3	19	125.4	100	125.4
Rest	1	5	50	250	100	250
			531.75	3113.275	100	3113.275
Efficiency%						
Losses in dc/dc	80			1900		Voltage drop *current*efficiency
Losses in diodes				500		Vf*current*2diodes
Motors						
Main motor	1	22	2.5	55000	8	8800
						20 drops, 1 minute each over 5hr mission
Servo	2	6	1.5	18000		negligible
Losses in diodes				1250	8	200
Total [mW]	14400	calculated for 5 hours operating time				
Current equivalent [mA]	650	calculated for 22V				
Operating Time[h]	7.5	22V,2200mAh, 3 packs 75% of capacity in low temp				
One battery failure[h]	3.75					
Two battery failure[h]	1.88					

Table 7. Power Budget

3.4 Experiment Setup

3.4.1 System

As shown in Figure 3.8, the overall system for this experiment consists of a MAIN Payload, which is rigidly attached to the gondola as well as a drop payload, referred to as the FISH, which is held in the MAIN Payload in the initial state of the experiment. The FISH is dropped from the MAIN Payload using a reel system, a *Daiwa Saltiga Surf Spinning 6000* fishing reel, which is capable of letting the FISH go into free-fall with minimal resistance from the line. The reel is controlled by an electric motor, which will be able to reel the FISH back up into the MAIN Payload after a drop and perform the slow reeling down of the FISH for taking measurements at various heights below the gondola. The braking of the FISH after a free-fall drop is also controlled by the same electric motor by using the built-in feature of fishing reels which automatically set the brake back on after the first turn of the handle after a cast. The releasing of the FISH into free-fall is achieved through turning the bail, with the help of a servo-motor, to release the line completely. As a redundant safety system, a line guide was installed which is intended to operate in case of failure in the reel system. The line guide is a simple winch, which in the case of its use, is powered by an electric motor and is able to perform the basic operations of braking, reeling up, and reeling down, but no free-fall drop of the payload.

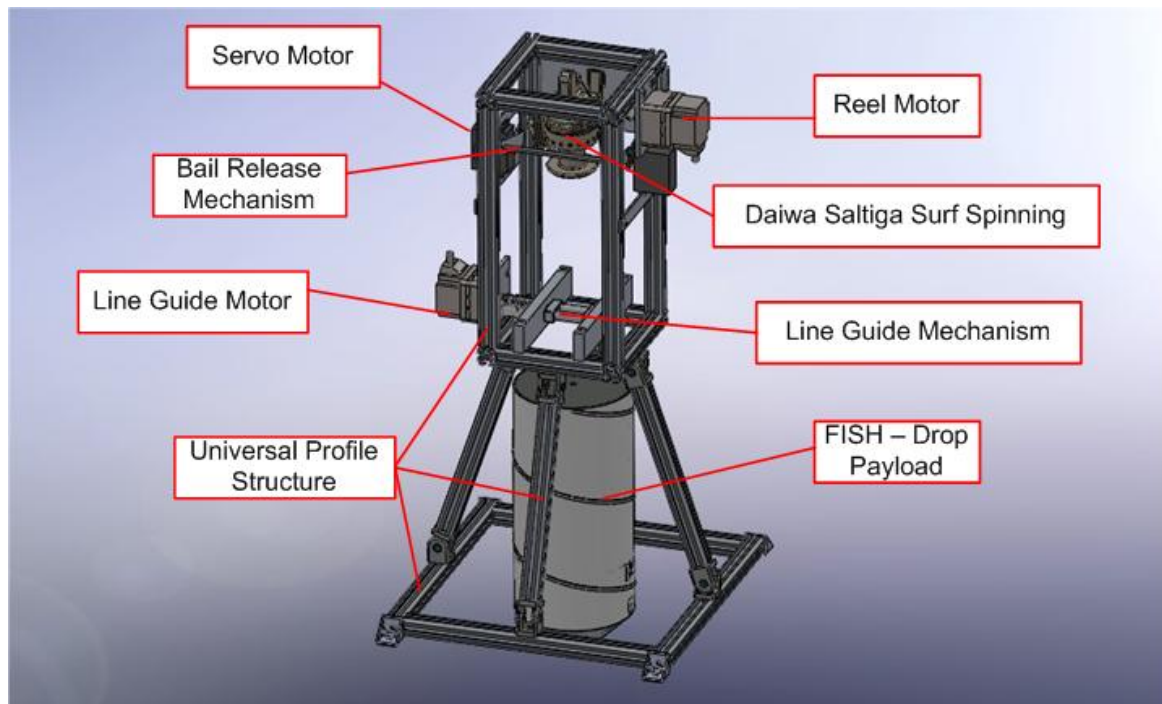


Figure 3.8 Experiment Setup



3.4.2 Interfaces

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3.5 Mechanical Design

The mechanical subsystem mechanically supports all of the reel.SMRT systems. It includes mechanical interfaces with the reel and motors, the MAIN Payload and the FISH and must satisfy all of the strength, stiffness, aerodynamic, stability, safety and interference requirements for the mission. The objective of the Mechanical Subsystem is:

Obj.M To provide the mechanical capability for a free-fall action and reeling up and down of the FISH in a safe manner and also to provide a robust housing for the components that will enable them to survive flight conditions, whilst providing an easily accessible structure for assembly and testing.

The external structure of the MAIN Payload and the FISH and the interfaces between them, carry the major loads and act as a barrier between the components and the external environment. The structure provides access to the components during testing and manufacture as well as the interface between sensors and the external environment. Additionally the structure must be built to withstand testing, storage and transportation. The internal structures support the circuitry and actuators. It also provides thermal and stress insulation from the extreme temperatures, pressures and conditions of the stratosphere and balloon flight. The mechanical design has been separated into 5 major components, which include:

- MAIN Payload
- Reel
- Line Guide
- Line
- FISH

These structures have been designed and analysed separately with the interfaces between them presented in Section 3.4.2.



3.5.1 MAIN Payload

The MAIN Payload was designed to support and hold all the components of the experiment. This included the reel system, the line guide system, safety guards, the bail release system, the batteries, the electronics, the insulation, and the FISH payload. The final design of the MAIN payload comes to a theoretically designed mass of 12.4 kg excluding the FISH, the electronics of the MAIN payload and the batteries. In order to simplify the design process, commercial off-the-shelf component use was maximised. Most of the structural elements of the MAIN Payload assembly rely on aluminium-extruded profiles available at *Solectro* at reasonable costs (refer to Appendix 5.7 for the complete product specifications). These products provide simple mounting and flexibility whilst keeping the weight to a minimum without significant loss of strength or stiffness. The analysis of the structure provided in (28) shows that these structures are strong and should provide the strength required to support the MAIN Payload's components. A structural analysis was performed to provide more confidence in the structural integrity and is found in Appendix 5.3. The conclusions of the structural analysis are as follows:

- The maximum compressive load, on the aluminium profiles, is 320 N which corresponds to a factor of safety of 215 with respect to the yield load of 68.8 kN;
- The maximum bending load, on the aluminium profiles, is 320 N which corresponds to a factor of safety of 9.6 with respect to the yield load of 3.088 kN;
- The maximum load, on the angle adaptors, is 320 N which is with a good margin of the specified maximum load of 1000 N;
- All fasteners and other connecting parts were oversized for robustness and will withstand the anticipated loads.

Figure 3.9 displays the structure of the MAIN Payload with primary components mounted on it. The design concept was to use a four corner pyramidal structure to provide a stable base for the experimental elements of the payload. The FISH payload can then be enclosed within the pyramid structure, the so-called FISH bay. The bay was planned to act as a funnel to reduce the effect of disturbances to the FISH through compliant geometries carved into the insulating expanded polystyrene, however, due to critical modifications to the interface between the line and the FISH payload to compensate the large braking impact force, the FISH could no longer be housed in the bay rendering the implementation of such a funnel useless and the idea was abandoned. The flight result data show very clearly that the flight does not generate significant disturbances to a hanging payload.

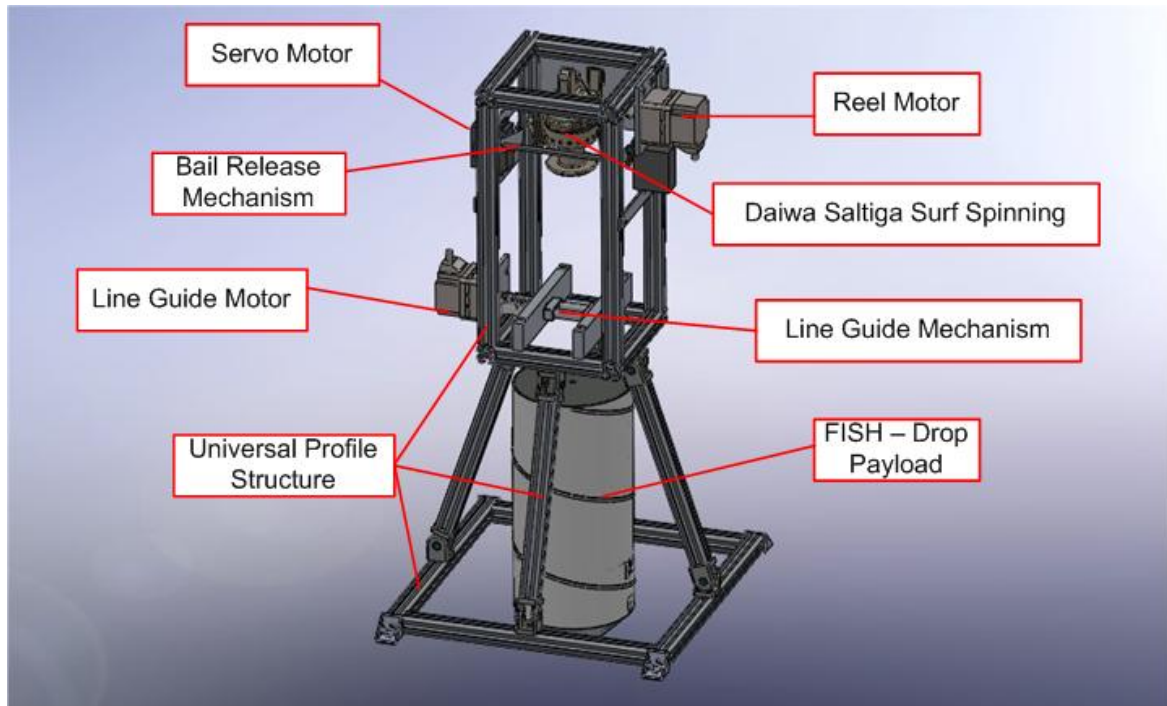


Figure 3.9 MAIN Payload Structure and Components.

To explain the overall design, from the top of the FISH bay and upwards, there are several distinct layers. First, a guard, a steel net for example, was planned as a safety mechanism in response to the Risk.M-M06. That is, in the case of a mechanical failure of the line guide system, the guard will prevent large broken-off pieces from falling from the gondola, however, tests have given us great confidence in the strength of the line guide mechanism and such guard proved to be superfluous and only could impede the main objectives of the mission. Then, the line guide system was installed in response to Risk.M-M01 and Risk.M-M02, its function is to provide means of performing the basic operations of reeling the FISH up, performing the slow reeling down, and securing the FISH for the ascent and descent phases of flight where higher vertical disturbances are anticipated. The third layer is comprised of another guard, similar to the first, which prevents broken-off pieces from a failure of the reel mechanism (Risk.M-M01 and Risk.M-M02) from falling from the gondola or impeding the operations of the line guide, which also proved to be superfluous throughout our tests. Finally, the reel system is fixed at the very top of the structure to provide maximum clearance for better of operation.

The insulation shall be composed of 50 mm thick low-density Expanded Polystyrene (EPS) which will provide the necessary protection for the harsh environment of the BEXUS flight section 3.6.1. This insulation was found at low-cost and suitable size from a local supplier in Kiruna. Figure 3.10 shows the MAIN payload from the outside as it is closed with the insulation box. To secure the

insulation panels, aluminium corner profiles are used which are 20 mm by 20 mm and were bought at low-cost from a local supplier in Kiruna. However, during the construction of the MAIN payload, the internal components, especially the electronics and motors reached too far out from the upper cage-structure and the insulation was extended to outside of these aluminium corner profiles, increasing the overall dimensions by 50 mm on every side. Also, due to the lack of structural strength of the corner profiles for transverse loads and the difficulties encountered in the attachment of the EPS, aluminium sheets were added to the inside face of the insulation panels to provide easier attachment of the EPS to the sheets and of the sheets to the corner profiles while provide transversal load strength. The final configuration of the insulation panels is shown in **Figure 3.11**.

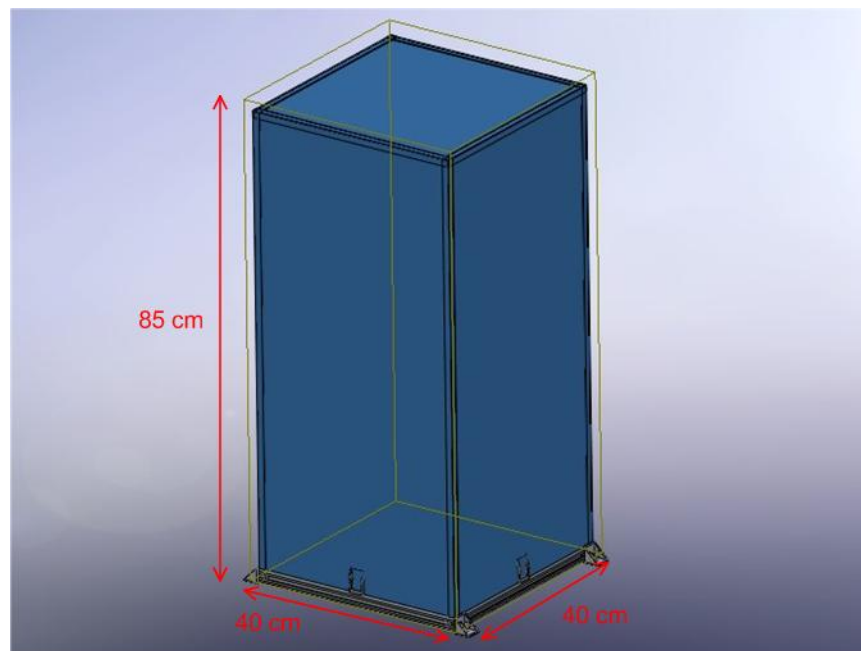


Figure 3.10 MAIN Insulation and External Dimensions



Figure 3.11 As-Built Insulation Panels. To the left, as mounted on MAIN Payload, to the right disassembled. The structure is predominantly composed of universal profiles. However, some parts are required for interfacing between the profile segments as well as for mounting the components of the experiment. Great efforts were put to seek components off-the-shelf with proper specification and availability in order to minimise the fabrication tasks. For example, angle adaptors, which were previously planned to be manufactured, were now obtained from the company *Item* from Germany through a Swedish supplier, namely *AluFlex Systems AB*.

Not shown in Figure 3.9 are the electronic components and batteries. These are, however, simple to mount and did not pose any challenge as space is readily available on either sides of the structure. The mounting of the electronics components was achieved with off-the-shelf standard plastic and metal electronics boxes. They were simply fixed to the aluminium profiles with M6 screws and matching slide nuts. Structurally, these no-load components did not pose a challenge.

The structural integrity of the MAIN Payload has posed some recent challenges from and since the critical design review in early June. A closer analysis of the interface between the MAIN Payload and the Gondola has led to some modifications of the mounting. The details of the findings have been submitted to ESRANGE's contact person Mr. Olle Persson on Jun 10th 2009 and may be found in Appendix 5.3 under "Supplement to the Mechanical Interference to the Gondola". The design modification in question concerns the mounting brackets originally planned in the design, which were found insufficient to withstand the possible loads. Consequently, the mounting was carried out by bolting sturdy aluminium corner sections on the side of the base square structure directly on the rail system of the Gondola, as can be seen from the Figure 3.12.



Figure 3.12 As-Flown Bare MAIN Payload mounted on Gondola via sturdy corner brackets. The frame is tilted as the side panels are not installed to support its shape in this image.

As a consequence of the initial tests of the structural integrity of the pyramidal structure of the MAIN payload, it was found that, due to the addition of multiple small errors in the final dimensions of the various parts, the symmetry of the structure is not perfect and the stability of the structure suffers. Under compressive loads, the structure was found to be as strong as expected, as Figure 3.13 demonstrates. However, in the presence of very high loads which are asymmetrical and include a vertical twisting moment, the structure demonstrated certain difficulty to remain straight as the angle adaptors tended to twist off-alignment. A simple, non-intrusive and redundant solution was found to remedy this problem: since the strength of the structure is not questioned under usual loading conditions, the solution lies in an additional structural element aimed solely at absorbing a twisting moment on the upper cage structure. The solution chosen was to use tensioned steel wires which would be attached from every bottom corner of the cage structure to the opposite corner of the bottom frame, and that in both directions. This solution was simple to implement, provided a maximum angle for the tension forces, and was redundant in the sense that only one pair of wires is necessary, but four pairs would be present. However, after more electronics components were added to the system, it was found that the benefits of this remedy versus its drawbacks when considering assembly procedures and testing encouraged the abolition of the extra structure. The team opted for a strict pre-

flight checklist during which all relevant nuts and bolts would be checked, and that proved to be sufficient to guarantee the reliability of the structure for the whole duration of the flight.



Figure 3.13 MAIN Payload's Structural Integrity Demonstration

3.5.2 Reel System

The reel system consists of the reel itself, its mounting, the reel drive, and the bail release mechanism, all present in Appendix 5.8 as both technical assembly and detail drawings. The reel that is to be used is a Daiwa Saltiga Surf 6000 Spinning reel. This is an off-the-shelf component whose main characteristics are summarised in Table 8. Refer to Appendix 5.7 for further details.

Daiwa Saltiga Surf 6000	
Maximum Brake Force	300 N
Mass	530 g
Gear Ratio	3.6:1
Reel direction selection lever	Yes

Table 8 Daiwa Saltiga Surf 6000 Main Characteristics

The choice of reel was motivated by multiple criteria, including:

- Reduced friction in the line when the FISH is in free-fall;

- High strength, needed due to the magnitude of potential loading in emergency modes of operation;
- Strong front-brake mechanism to decelerate the FISH;
- Ability to control the ascent and descent of the FISH;
- Ability to control a zero-backlash anti-reverse brake for power-off risks;
- Ability to work at high altitudes, with top-quality seals and bearings;

The reel chosen was the best compromise between all of these attributes, irrespective of price. In order to keep the integrity of the line strength, the line is attached to the reel's barrel using a Locked Half Blood Knot which maintains 92 % of the strength of the line at the attachment point (29).



Figure 3.14 Daiwa Saltiga Surf 6000 Reel

3.5.2.1 Friction Analysis

The selection of a fishing reel for this experiment was motivated by the extreme low tension from the reel after the release of the line. By opposition, a classical reel mechanism such as a winch or any other mechanism involving a pulley-type coupling to the line's dynamics can absorb a large amount of energy through friction and kinetic energy build-up. Even a quasi-frictionless bearing cannot help to prevent the kinetic energy built up in the unwinding of the line to slow down the motion of a small weight under free-fall. The advantage of the fishing reel lies in the fact that the line is released completely from any coupling to the barrel. The working principle is based on a bail, which winds the line around the barrel rather than the barrel turning to wind the line. The bail is then allowed to swivel and release its hold on the line completely and the line thus falls out of the barrel without inducing any kinetic energy build-up or any significant frictional forces.

The friction force between the line and the reel as the FISH is being dropped into free-fall is very difficult to estimate since it depends on many factors such as the

speed of fall, the angle between the line and the reel, the actual winding on the barrel, the coefficient of friction between the line material and the edge of the barrel and between the line material and itself, as well as many other physical effects. Some will be minimized in design, for example, as shown in Figure 3.14, the line was reeled all the way to the edge of the barrel to minimize the contact area. One can start to analyse the friction on the line by considering two dominant effects: the friction between the line and the edge of the barrel; and the friction amongst the windings of the line as it gets unrolled.

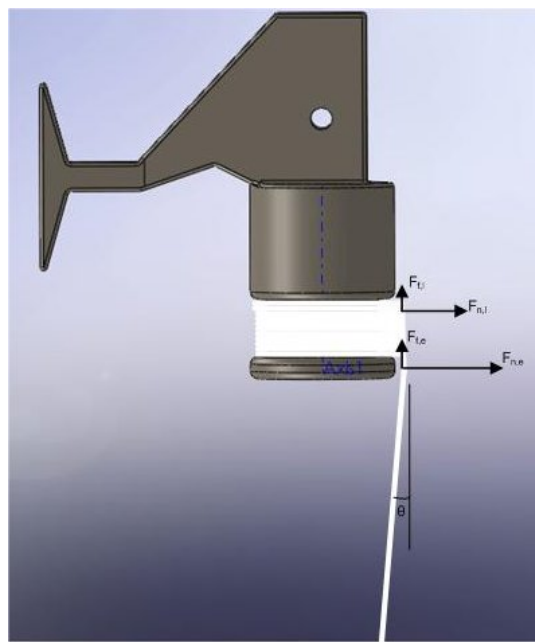


Figure 3.15 Friction Forces on Line Release

First, the friction between the line and the edge of the barrel is expected to be negligible. This comes as a result of considering the two factors that determine the friction force: the normal contact force and the coefficient of friction. The latter is expected to be very small due to the quality of the selected reel. It is one of the advertisement points of the manufacturer to be able to ensure very low resistance on a line when casting. Hence, the coefficient of friction can easily be estimated below 0.05 since the selected line is also advertised as smooth and frictionless. The main factor to justify neglecting the friction between the line and the edge of the barrel is the small scale of the normal force. The pulling force, coming from the FISH's dropping acceleration, is transferred to a normal component to the edge of the barrel through the angle θ , see Figure 3.15. The angle is made small due to the small size of the barrel in comparison to the distance to the bottlenecks created by the line guide and the guards, which is of the order of a 1:10 ratio. The residual normal force is consequently very small and the induced Coulombic friction negligible. However, the friction force does remain linear dependant on the amount of line which is trailing behind the FISH, it yet remains to determine to what extent it can remain negligible. Testing would be required to determine the



tension and the angle of the line, which is strongly dependant on the wave propagation through the tether.

Second, the friction force between the falling line and the windings on the barrel is also negligible through similar arguments as the aforementioned friction force. Again, due to the assumed smoothness of the line, the coefficient of dry friction of the line material with itself is assumed to be very small. Then, the scale of the normal force on the line is again very small because the path of the line is straightened by the edge of the barrel. Another favourable physical effect is the tensioning of the wound line. As the line is in tension on the barrel, during the winding of the line while, when it is released, the elasticity of the line will tend to straighten it and it will naturally expand away from the barrel, although the extent of the contribution of this effect is not known to a great extent and it would be an interesting side investigation to determine its effect through testing, if time and expense allows. Furthermore, this friction force is stochastic because of the unpredictable details of the line winding on the barrel. Depending on the order at which the line is rolled on the barrel, the impedance of the one turns over the release of the other turns is highly unpredictable and it will be interesting to observe if any quadratic chirp effects are observed on the acceleration measurements. In summary, it was determined that this reel system is the best choice for minimizing the resistance to the free-fall of the FISH, not to mention its practical advantages.

3.5.2.2 Brake Analysis

The brake of the reel is a very important device that is needed to stop the descent of the FISH after its free-fall. This brake needs to be set before the mission has started because it cannot be changed during the flight, due to the front-adjustment which permits no autonomous adjustments. Thus the correct brake strength is essential to know before the flight starts. The two constraining factors that affect the brake strength are the length of the line and the strength of the line. The FISH has to be stopped before the line runs out, at 200 m, but if it is stopped too quickly then the force on the line will cause it to break. Thus a fine balance is needed.

Brake Force	120 N
Stopping distance	11 m
G's experienced	<6 G

Table 9 Reel Brake Characteristics

The analyses are shown in Appendix 5.2. Tests in the mission environment were undertaken to find the exact position at which to adjust the reel's brake and it was limited by the strength of the line to about 1.5 time the minimum brake strength to hold the weight of the FISH which considerably reduced to possible drop length. Moreover, the amount of line wound on the reel was limited to 70 m due to the fact

that low temperatures made the barrel of the reel shrink more than the line loops, releasing the tension that holds the line on the barrel, the possible unwinding length of the line had to be limited and by doing so, the possible length of the drop as well. From then on, the drop length was planned to be starting with a first drop of about 10 m up to a maximum final drop of 30 m.

3.5.2.3 Reel Motor Selection

The reel motor purchased is a brushless DC motor with 24 V input and rated at 50 W input at a nominal speeds up to 202 rpm with a rated torque of 2.2 Nm under continuous operation (please see Appendix 5.8 for more details on the model EC-45 Flat 251601 and GP 42C 203119). This was determined to be sufficient, with a safety factor higher than two, for all operations required by the reel system, especially reeling the FISH back from at most 100 m down within two minutes, as originally planned. The manufacturer of the product is the American company 'Maxon Motors's, which has Swedish suppliers; they provide industrial grade motors, compliant to many industrial standards, which are available at reasonable prices. The choice of brushless motors was based on reducing EMI effects on the MAIN Payload and the gondola, as well as reliability issues with brushed motors that would not respond well to the Stratospheric environment, according to the contacted manufacturers.

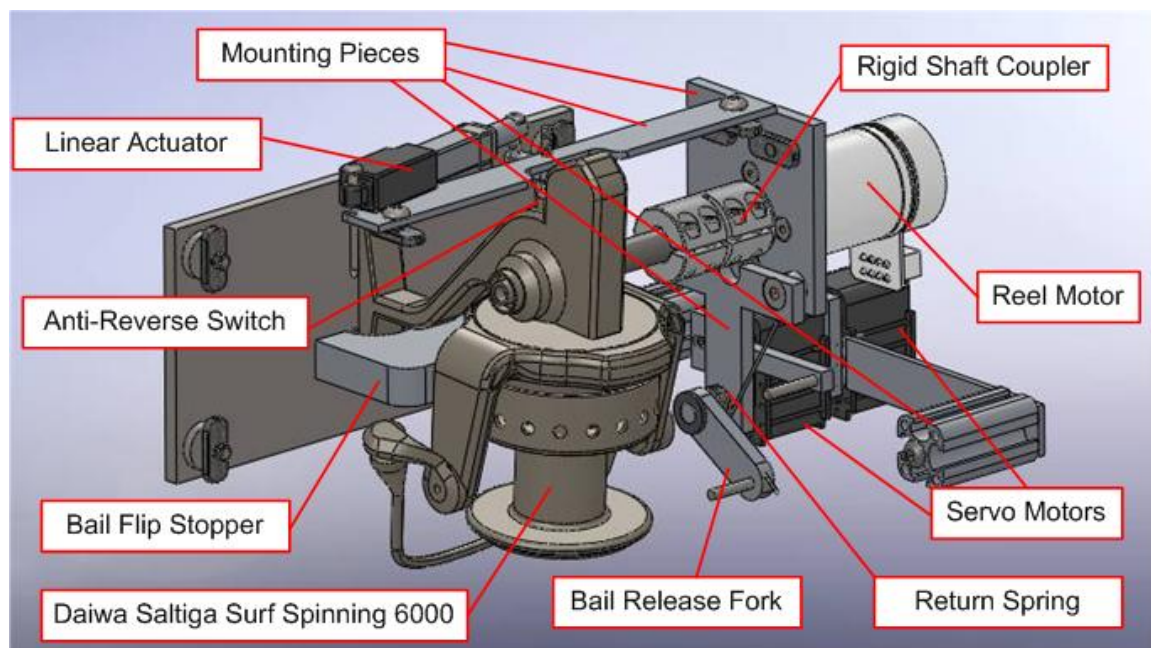


Figure 3.16 Reel System

Since the critical design review, the bail release mechanism (shown above as part of the reel system) has been completely redesigned in response to a strong incentive to review the redundancy configuration previously planned and to address an experimental finding with regards to the intrusion of the bail release



mechanism with the line. The operation of the Reel System is demonstrated by a video of the reel.SMRT system on Youtube: <http://www.youtube.com/watch?v=uYF9c46WcGs&feature=related>.

The simple mechanism previously designed consisted of a fork running across the reel which would drag the bail open by the action of two servo motors on each side of the reel. One major issue with this original design was raised at the critical design review, where it was identified that the failure mode corresponding to a servo motor being blocked in one position may cause the redundancy design to fail. Hence, the redundancy was serialized in the sense that one servo was mounted on the output of another, thus ensuring that if one servo stops working, the other can perform the operation instead. Furthermore, as a result of test M.7A, the servo motor was reselected for the *Robotis Dynamixel AX-12* which is a daisy-chain serially controlled servo which provides enough strength to open the bail as well as imparting bonus additional features such as position feedback, temperature feedback and status flags.

As a result of test M.7B, two important design changes were motivated. First, it was determined that in order to have sufficient strength to open the bail, the speed reduction causes the servo motor to return too slowly back to the clearance position, and consequently, the designer has opted for a decoupled mechanism that is pushed by the servo motor to grab the bail and open it, and then, be released from the servo motor drive to flip back to the clearance position by the action of a spring. The decoupling of the mechanisms was achieved via eccentric lever arms, that is, the servo's output is centred slightly away from the centre of rotation of the bail. As the servo rotates, the pin at a particular radius on the servo's lever arm will contact the bail release lever which has a shorter radius but is centred at the bail's centre of rotation. As the bail is opened, the pin of the servo's arm will go beyond the radius of the bail release lever, which will then flip back to the original position via a return spring.

The second result of test M.7B was the need for a less intrusive design on the bail. The motivation was to avoid impeding the free-fall of the line just after the opening of the bail. Since the line is on the pulley at one side of the bail, if the bail release fork is limited to the other side, the chance of the line ever reaching the bail release fork is null which only became obvious during testing. The servo motors are mounted on either side of the reel using simple Aluminium plate of 3 mm thickness and 20 mm width, which are sufficient to hold the loading induced by the servo's output torque with a factor of safety of 32 (for calculation please see Appendix 5.3).

However, the above-described mechanism did not make it to the as-built configuration due to the findings of test M.7C which showed, to our great disappointment that the selected servo motor (*AX-12*) was still not strong enough to release the bail when under a maximum load corresponding to the mass of the FISH payload. And hence, the bail release mechanism was redesigned yet a third time to include the strongest servo-motor available that could be integrated to our

systems, *dynamixel RX-64*, which are similar in nature to the *AX-12* model but with 18 V power supply and much increased output torque, up to 64 kg-cm. Because of the large size and price of these servos, the redundancy scheme had to be abandoned and the final, as-built, mechanism is shown in Figure 3.17 where the servo is directly connected to the bail release arm (no more decoupled mechanism) and is rigidly mounted on the side of the reel opposite to the motor for clearance issues. Note that this design change does not appear in the technical drawings because of the relative simplicity of the design and the very late phase in which it had to be built, time no longer allowed for conceptual design on CAD.

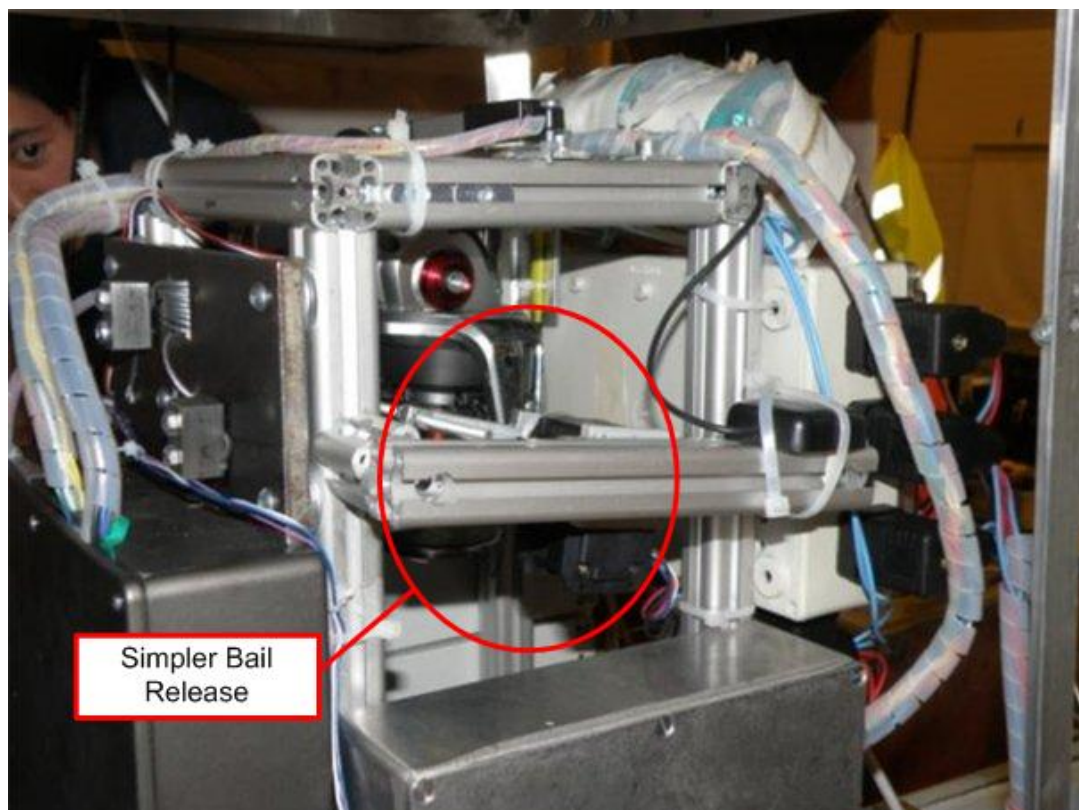


Figure 3.17 Side view of the top part of the MAIN Payload, showing the as-built bail release mechanism. The structural member is at an angle to the horizontal as it was hand-adjusted to achieve optimal servo positioning for the opening of the bail.

The bail closing mechanism is not provided internally by the reel itself, which came to a surprise midway in the design phase as it was assumed, from talking to experts, that all reels had an automatic bail closing mechanism. In spite of this setback, a simple solution was found by the simple addition of a so-called bail flip stopper which is simply a slab of aluminium at the base of the reel which hits the lower part of the bail as it is wound back. As it hits the bail, it will close and the brake will engage normally. This also has the effect of reducing the requirements on the holding torque of the reel motor since it now has the chance to build some kinetic energy before hitting the bail flip stopper, although to what extent is unknown.



An additional modification to the mechanism occurred as a consequence of critical design review feedback as well as trade analysis between power consumption and risk management. The underlying issue, pointed out at both the preliminary design review and critical design review, was about the case of power failure (considered as a double failure case as the entire power electronics are fully redundant). In case of power failure during an operational phase in which nothing holds the FISH payload besides the reel, the motor which holds the reel's shaft stationary would not be able to hold anymore and the FISH would fall, held only by the back-EMF of the motor. Two solutions were considered: the addition of a safety power-off brake on the reel motor or the use of the anti-reverse switch at the back of the reel. The former is simple to understand and implement, however, the highly increased power consumption during motor operation of 15 to 20 Watts and the high cost of such safety brakes made the team very reluctant to choose this option. The second option deals directly with the objectives of this mission. The idea is that in order to achieve the secondary objective of performing tethered measurements, via the so-called slow reel mode, The reel is required to be able to reel down in the reverse direction, i.e. the reel's anti-reverse switch needs to be off during this operational mode. If the anti-reverse switch was kept off for the whole flight, the task of holding the FISH in place, for the operational modes of concern here, would rely entirely on the reel motor. The obvious alternative is to add the capability to turn the anti-reverse on and off during the flight. This option was chosen due to the fact that it is simple and inexpensive to implement, does not consume extra power during the reel motor's operation, and consists of an acceptable risk since the only remaining failure scenario is that the power failure occurs during the slow reel mode which will be performed before the drop mode and therefore a safety risk would not be imposed.

The design of the anti-reverse switching mechanism involves a simple analog linear actuator (Firgelli L12-30-210-12-P), which actuates the reel's switch via a small axis above the switch. The interface to the switch was realized with compliant geometry which was built directly to match the reel's switch and hence does not appear in the technical drawings.

The mounting elements of this design are very straight forward. The elements of the reel system are mounted on the universal profile structure which surrounds the area where the reel is placed. Mainly built of custom components in aluminium, the mounting pieces are easily interfaced to the profiles using M6 screws and matching sliding nuts, also purchased from *Solectro*. The sliding nuts also provide the flexibility to adjust the design to exactly match the reel's geometry or motor selection at assembly time.

The reel is mounted on a thick 6 mm steel plate, which was determined to provide the necessary strength to hold the loads that could reasonably be imposed on the reel. With a loading condition of 150 N, corresponding to about 5 G in the upward direction applied to the FISH (~1.8 kg) corresponding to the brake setting and 10 G in the upward direction applied to the reel (~0.5 kg), the mount plate remains



within a factor of safety of 3. The reel is attached to the plate via steel straps which are structurally equivalent to or even improved from the usual mounting of a reel on a fishing rod. The idea here was to minimize the destruction of the reel for preserving its worth; however, if tests show any weakness of this arrangement, the reel can also be fixed to the plate otherwise, to a more or less destructive degree.

The reel motor is also mounted with a 6 mm thick aluminium plate which will easily bear the loads from the weight of the motor, expected to be less than 2 kg, even under 10 G of vertical loading, i.e. about 200 N load will hold within a factor of safety of 3. The mounting configurations of both the reel and its motor are thought such that, through the sliding nuts, the motor can be displaced in the horizontal direction while the reel can be displaced in the vertical direction which will be useful when aligning the axes during the assembly.

A final remark on the mounting would involve the assessment of vibration. One could argue that the mount of the motor is prone to vibration, e.g. cantilever modes, however, the coupling to the reel through the drive shaft will break those modes of vibration and will secure the whole reel and motor coupled-structure.

3.5.3 Line Guide System

The line guide system was implemented as a redundant mechanism in the event of any failure in the reel system; the line guide system is a purely a safety feature. The functionalities of the line guide are limited to reeling the FISH up and down, that is, no free-fall is possible through control of the line guide. The line guide also serves the purpose of a redundant braking system (Risk.M-M03, Risk.M-M04, and Risk.M-M07). The design of the line guide is very simple: It consists of a motor, very similar to the reel motor, and a "cage" structure which can be turned and the line winded around it. In order to stop the FISH in free-fall, the line guide is turned, and consequently, impeding the fall of the FISH to an eventual complete stop. Through analysis, it was determined that the maximum load generated by the friction on the cage pins are limited to 100 N per pin, but to be safe, as the analysis of these dynamics is very difficult, the structure was designed to withstand 200 N of force on each pin with a factor of safety remaining above 5 for all components of the assembly (please refer to Appendix 5.3 for detailed finite-element analysis). To reel back the line, the line guide is simply turned all the way until the FISH is back inside the MAIN Payload, an operation which may be performed at approximately one third of the speed of the reel system. Depending on the conditions after the recovery from either of the aforementioned failures the mission can continue, but is limited to the slow lowering of the FISH below the gondola before normal operations may recommence.

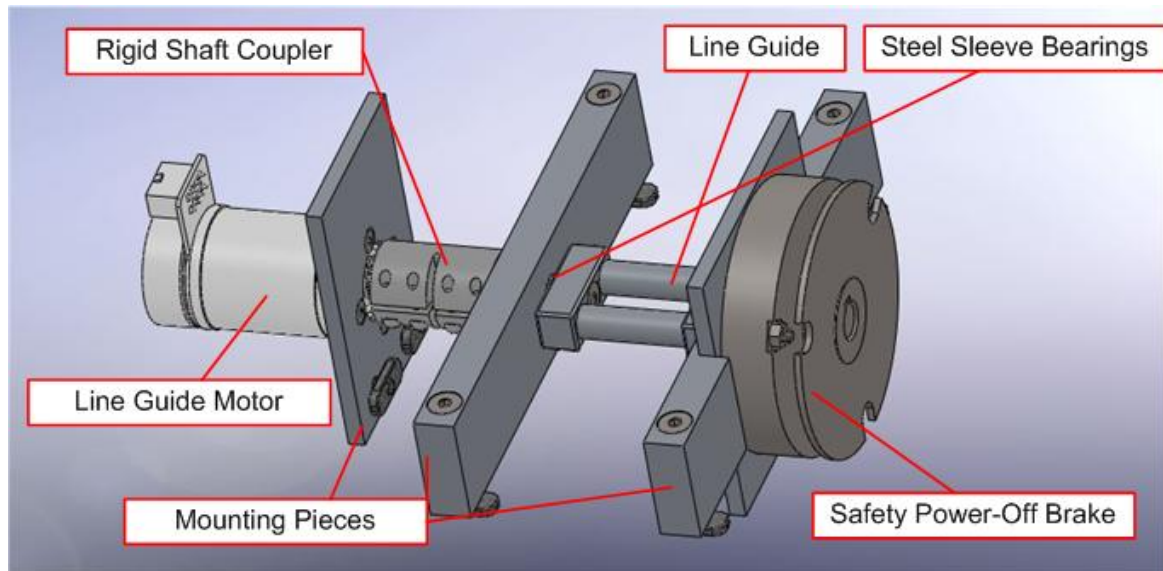


Figure 3.18 Line Guide System

As of the specifics, the motor selected to power the line guide is the same as for the reel system (see Appendix 5.7 for model EC-45 Flat 251601 and GP 42C 203119). The safety brake is present to ensure a powerless hold of the line guide which is used whenever the system is not operating in order to hold the FISH payload in place or to keep the line guide horizontal to avoid interfering with the drop. The safety brake selected is the RNB-0.8G from Ogura (please refer to appendix 5.7 for the datasheet). The bearings used to support the line guide are bronze-solder-PTFE-coated steel sleeve bearings which support high loads and good rotational speeds, operate over a large temperature range, and avoid the use of any lubricant. The custom pieces will again be machined from Aluminium. They were design for simplicity of machining as opposed to the previous design presented at the preliminary design review. The mounting is achieved with oversized aluminium plates of 15 mm thickness. The “cage” assembly will be composed of aluminium pins and small slabs which are fastened together with flat head M6 screws.

3.5.4 The Line

The **Platypus Super-Braid** (30) is the line chosen to fulfil the needs of the reel.SMRT project. It is composed of Ultra-High Molecular Weight Polyethylene (UHMWPE) from a company called Dyneema (31). It has a 192 N maximum load (reference Test M.3) and is able to withstand temperatures below -150°C with minimal compromising effects on the strength of the line (31). It is also lightweight with a density of 0.97 g/cm^3 (31), which reduces the effects of the line momentum on the FISH when in free-fall. It is pliant, has a very small line memory and resistant to UV (31).

The line design is fairly simple with with the majority of the design factors dependant on the strength of the superbraid. The line has a few components attached to it to make sure the it is able to survive the complete mission. The components of the complete interface from the reel to the FISH are as follows
orded from the reel down:The line itself

- Dampener Cord
- Swivel
- The 5 braid line

The line itself is approximately 100 m long and it is directly connected from the reel to the dampener cord via a carabina which is located approximately 0.5m from the tail of the FISH. Attached to this is the swivel mechanism this and then the 5 braid line. This complete mechanism is then connected to the FISH to ensure that it is always attached to the MAIN for the complete mission.

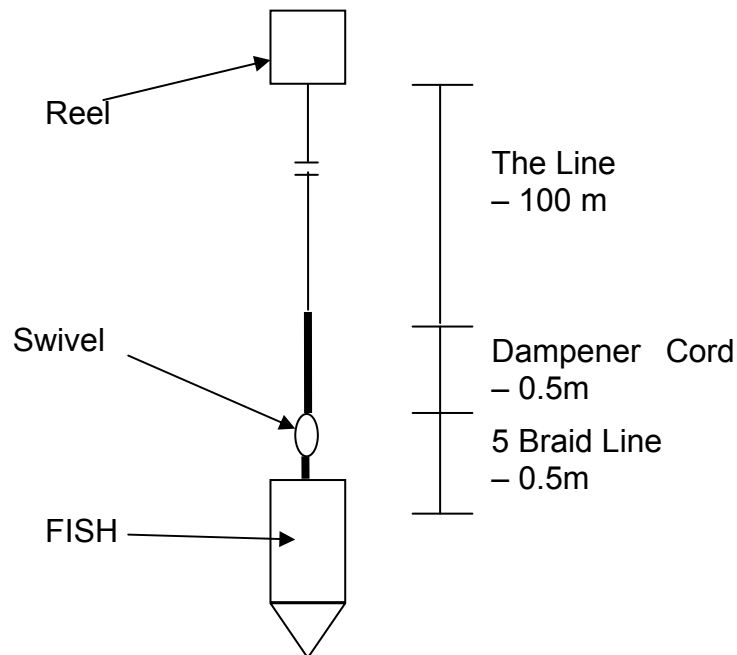


Figure 3.19 FISH and Line System

During the different phases of of the mission there are different stress placed upon the line. The two critical phases are during the:

- Deacceleration of the FISH
- Housing of the FISH



These two phases have been analysed and are calculated in Appendix 5.3. The results of this analysis are summarised in Table 10.

Critical Phases	Critical Forces
1. Deceleration	80 N
2. Housing	157 N

Table 10: Critical Forces for the Line During the Critical Phases

For the first critical phase, the deceleration shall be controlled by the brake and so are stress on the line. This brake shall be set to 40 N braking force, which is designed to ensure that the line stresses are always under the threshold. Even if multiple G's are placed on the FISH while it is decelerating, the brake will merely let more line out instead of increasing the stress through the superbraid line. The critical force that is experienced in this phase will consequently be met by a Factor of Safety of 2.5.

During the second critical phase the forces are larger than the first phase. In this period the FISH will be housed with the line wrapped around the line guide, thus all the stresses will be taken off the reel and placed onto the line guide and the lower segment of the line. The Factor of Safety for this stress is 1.25 with the dampener not taken into account, thus in practice the FS will be increased due to the time in which the stress was absorbed over. These results are summarised in Table 11 and Appendix 5.3.

Critical Phases	Factors of Safety
1. Deceleration	2.5
2. Housing	1.25

Table 11: Critical Factors of Safety for the Critical Mission Phases with the dampener not taken into account

3.5.4.1 Dampener Cord

The Dampener Cord was an added feature due to the ever increasing mass of the the FISH and when the Test M.15 was failed. This Dampener Cord absorbs the majority of the shock when the FISH was caught allowing for the line's maximum stress to be reduced. A Safety line was also placed around the Dampener Cord so if it is broken a 5 braid line will then absorb the load.

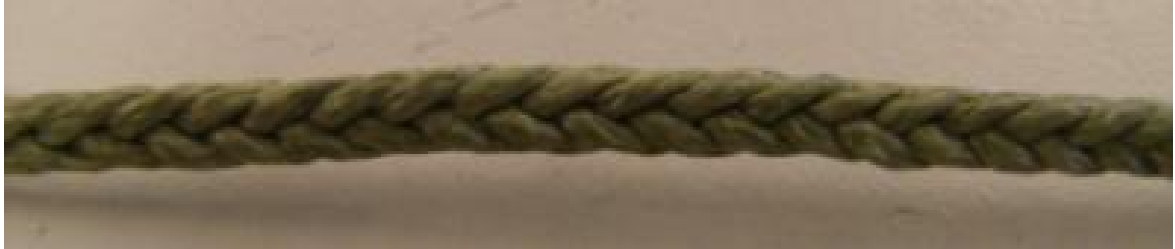


Figure 3.20: 5 Line Braid (five of the lines have been braided to create a very strong tether)

3.5.4.2 Lower Segment

For the tether's lower segment, the design is aimed to be very durable due to the amount of use this area gets along with wear, thus a 5 line braid segment with a swivel and carabineer attached either end (shown in Figure 3.21). This lower segment is 0.5m in length total. all attachments were via a blood knot with the loop fed over itself to create a strong bond (the image is shown in Figure 3.22).



Figure 3.21: Lower Segment of the Line that is Attached to the FISH

The purpose of the swivel is hold a very large load while being able to rotate around one axis. This stopps the line from becoming tangled when the FISH rotates on the way down or, more importantly, on the way up. This swivel is then attached to another 5 line braid which is fed through a plastic tube. The plasic tube is used to stop the line from cutting through the Radio insulation that is located around this part of the line. The Radio insulation is discussed further in this section. A carabineer is attached to end of the last segment of the 5 braid line (shown inFigure 3.21), which is designed to be a easily removable device that can attach itself to the parachute deployment mechanism. This lower segment has been strength and thermally tested (Test No M.3, M.4, M.13, M14) to make sure the line and interfaces survives the environment that it will experience.



Figure 3.22: A Blood Knot is Made to Create a Loop which is Then Fed Through the Ring and Then Over Itself

3.5.5 FISH

The FISH is essentially a sensor package and the structure is designed to protect the electronics from mission hazards whilst reducing the effects of the atmosphere on the results. The design of the FISH is shown in Figure 3.23.

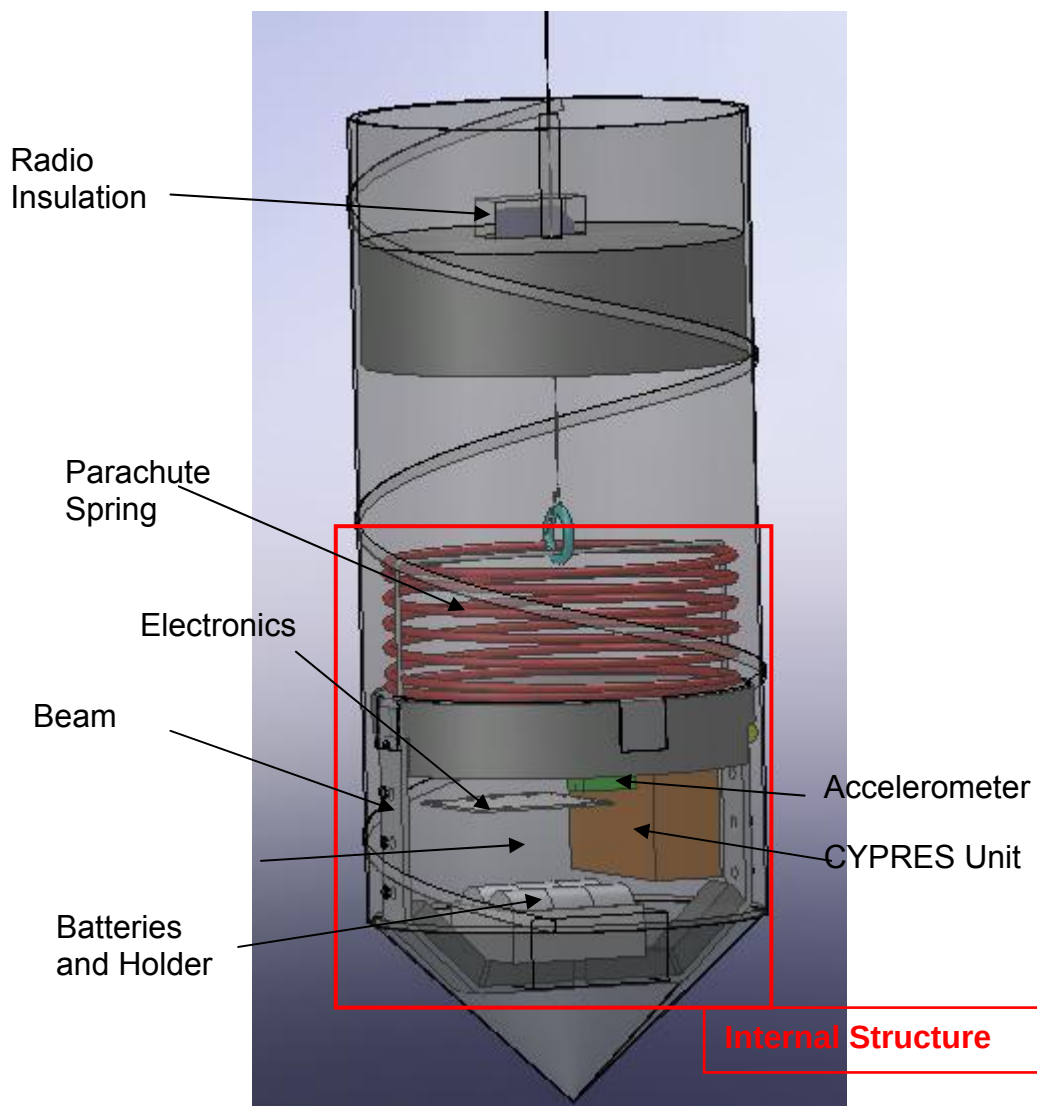


Figure 3.23: FISH's External Design

A general summary of the design is shown in Table 12.

Mass	1.6 kg	Appendix 5.1
Length	400 mm	Appendix 5.7
Width	160 mm	Appendix 5.7

Table 12: Overall FISH Characteristics

The FISH is composed of multiple components that are joined together to give the optimal layout whilst still maintaining structural integrity. This structure is comprised of two parts;

- the external and
- the internal structure,

which are able to be independently removed from one another to allow for maintenance of the electrical equipment inside.

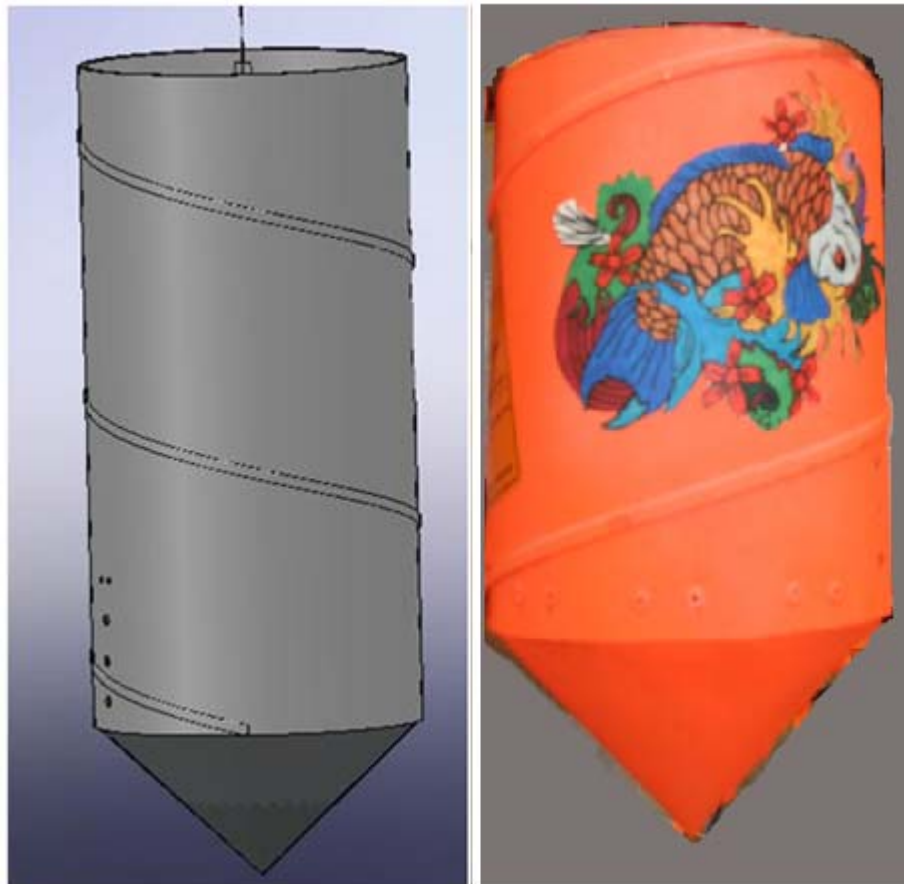


Figure 3.24: External Design of the FISH a) CAD Drawing, b) Real Structure

The external structure consists of the skin, nose cone and nose insulation (Figure 3.24), which are designed to keep the aerodynamic shape of the FISH whilst providing the support and structural integrity for the duration of the mission (Req.O.M.1). This skin shape produces a $C_d = 0.2$ (Appendix 5.3) and a more accurate value shall be obtained through wind tunnel tests. The skin is a solid Aluminium clad pipe with a width of 160 mm, allowing it to fit the parachute inside. This pipe is strong, ridged and has a high strength to weight ratio allowing for this member to be a significant load bearing item while holding the complete FISH together. The nose cone is attached to the skin along with the insulation. A nose cone is implemented because it maintains good aerodynamic capabilities whilst being easy to manufacture. The insulation design will be discussed in the Thermal Analysis section (Section 3.6.2).

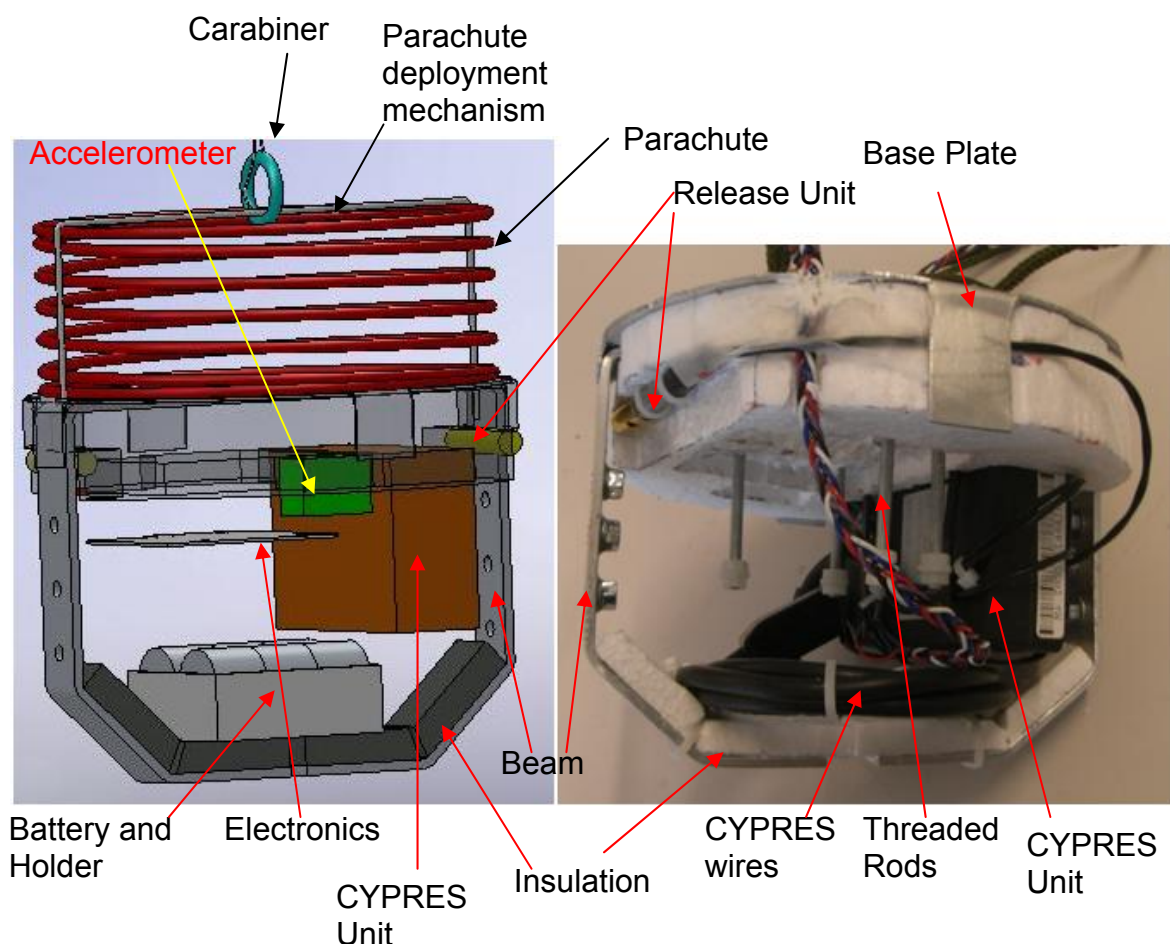


Figure 3.25: Internal View of FISH

When the external structure is removed only the internal section is left which is shown in Figure 3.25. The internal structure consists of a Beam, a base plate, two plates, and insulation. The base plate along with the beam is the primary structure of the Internal FISH which is shown in Figure 3.26. Due to its configuration, the

structure is able to withstand the large forces that will be experienced during the mission (Req.T.M.1). All components are attached to this structure due to its structural integrity with majority of the components attached to the base plate alone. The skin of the external structure interfaces with the beam via three 5mm bolts on each side which is able to provide the strength for the skin to remain attached during all mission loads. All components that are attached to the base plate are cable tied in via pre drill holes in this plate except for the PCB which are fastened via four long threaded rods shown in Figure 3.25.

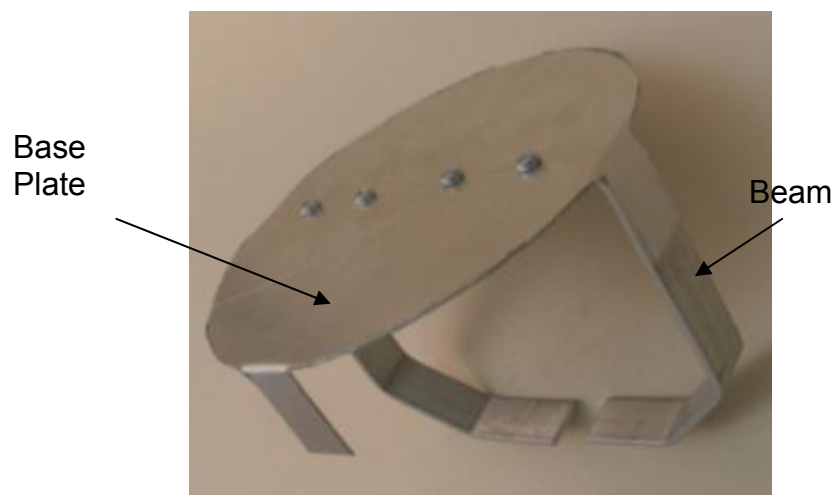


Figure 3.26: Base plate and Beam attached

At the bottom of the beam the batteries will be physically attached to the strut. The wires from this device were placed through the insert and directly connected to the electronics board.

Due the skin being made of a metallic material, the radio transmitter/ receiver may have difficulty penetrating the skin. Thus the radio is attached to the line located near the top of the skin (Figure 3.27). In this position the radio will have a clear view of the gondola thus the transmission has the highest chance of a successful. This device will be surrounded by a minimum of 35 mm of insulation to protect it from the thermal environment along with the wires that connect it to the electrical circuit board will be fed through the cutter to make sure it doesn't interfere with the release mechanism of the parachute. To make sure the insulation does not have any effects on the radio the Zigbee will be covered in plastic to reduce the chance of static shocks.

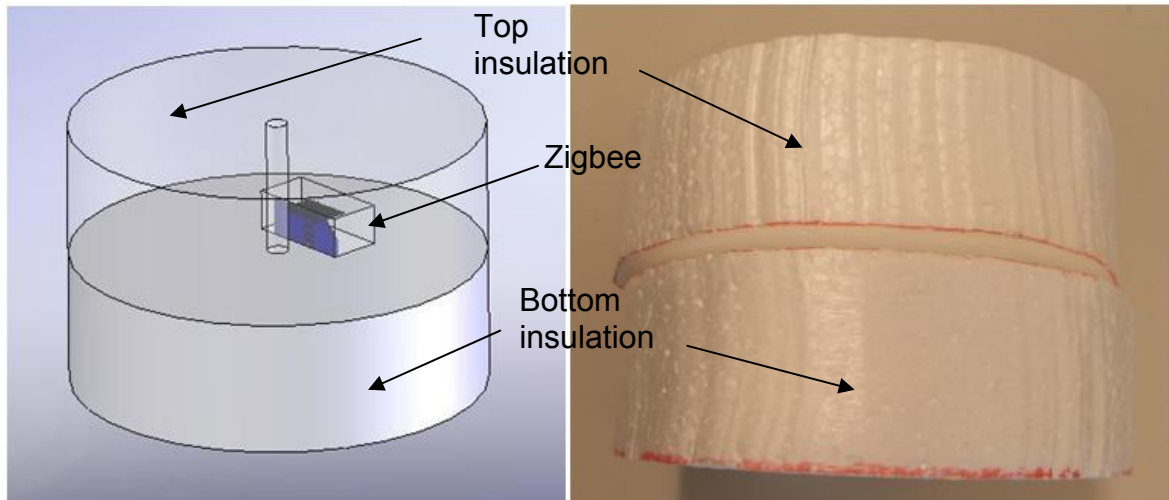


Figure 3.27: Radio Insulation a) CAD Drawing and b) Real Insulation

This Radio insulation will be attached to plastic tubing that is located around the 5 braid line segment thus maintaining its position during the flight. Also no forces will be placed through this insulation during the mission due to its configuration. All the stresses will be displaced through the line that is located at the insulations centre which is then connected to the FISH directly.

Main Design Factors

The CoG was lowered mainly by moving all the internal components as close as possible to nose of the FISH (Figure 3.23). The heavier components are situated closer to the nose while the lighter devices are located higher up (except for the parachute). Also, placing the CYPRES Unit and PCB on the same level as each other helped reduce the complete size of the internal structure and so helped lower the CoG. The main hindrance of reducing the CoG even more is the mass of the skin and parachute. These are both heavy items which have a local centre of gravity closer to the tail thus requiring a large amount of mass near the nose to counter this.

For the Centre of Pressure design, the skin of the FISH was made as long as physically possible such it could still be housed inside the MAIN Payload. The nose cone was also made relatively short, primarily to allow for more of the internal components to be situated closer to the nose.

All these design factors have been accumulated to increase the static margin to the largest possible distance hence achieving the most stable design.

3.5.5.1 Parachute Safety System Design

After the risk analysis it was assessed that a parachute was needed on the FISH for the proper implementation of a safety system (M-M08, M-M09) and to satisfy requirement Req.O.3. The parachute safety system requires two devices to be

implemented maintain the maximum safety of the overall mission. These two devices are: the parachute itself and the parachute release system.

Parachute

The parachute chosen is the pilot chute which is normally used for a common skydiving parachute shown in Figure 3.28. This is a COTS product which is very important due to the increased reliability of the device. The overall specifications of this parachute is:

Mass	370g
Length	780 mm
Length – Compressed	50 mm
Release Mechanism	Spring loaded
Diameter	0.66 m

Table 13: The Parachute Characteristics Summary



Figure 3.28: Parachute Expanded

The parachute is stored in the middle of the FISH above all the electronics to lower the CoG. Above this area is nothing except for insulation which is attached to the line thus allowing for the parachute to have a hindrance free release. It is also surrounded by the skin which acts as a guide for the parachute to be deployed

(Figure 3.23). The chute will be held into place by a single high strength line and will be discussed further in next section. Once the release mechanism is triggered the line will be cut and the spring will push the parachute up and allowing it to fill up with air. The parachute will be tied to the Beam of the FISH via a paracord which is attached to bottom of the parachute. These types of shock cords are very common for parachutes due to its high stress capacity. This is a very basic and simple type of release mechanism allowing for less complexity and thus higher reliability. This type of parachute is also able to be launched facing any direction along with a spin hence reducing the probability of the failed deployment.



Figure 3.29: Parachute Compressed

In the case of the parachute being deployed, the FISH will be slowed down to the terminal velocity at 7.14 m/s (25.7 km/s), where the C_d is assumed to be 1.5 for a dome shape parachute (32). The calculation of the terminal velocity is shown below.

$$V = \sqrt{\frac{2 \times W}{C_d \times \rho \times A}} = 7.14 \frac{m}{s}$$

$$\text{Weight} = 1.6 \times 9.81 = 15.7 \text{ N}$$

$$C_d = 1.5$$

$$\rho = \text{Air density at Sea level} = 1.2 \text{ kg/m}^3$$

$$A = \text{Surface Area} = 0.33^2 \pi = 0.342 \text{ m}^2$$

Parachute Method of Release and Design of Parachute Housing

Due to the desire to increase the reliability of the deployment mechanism the design for has been changed. This design for this system is shown in

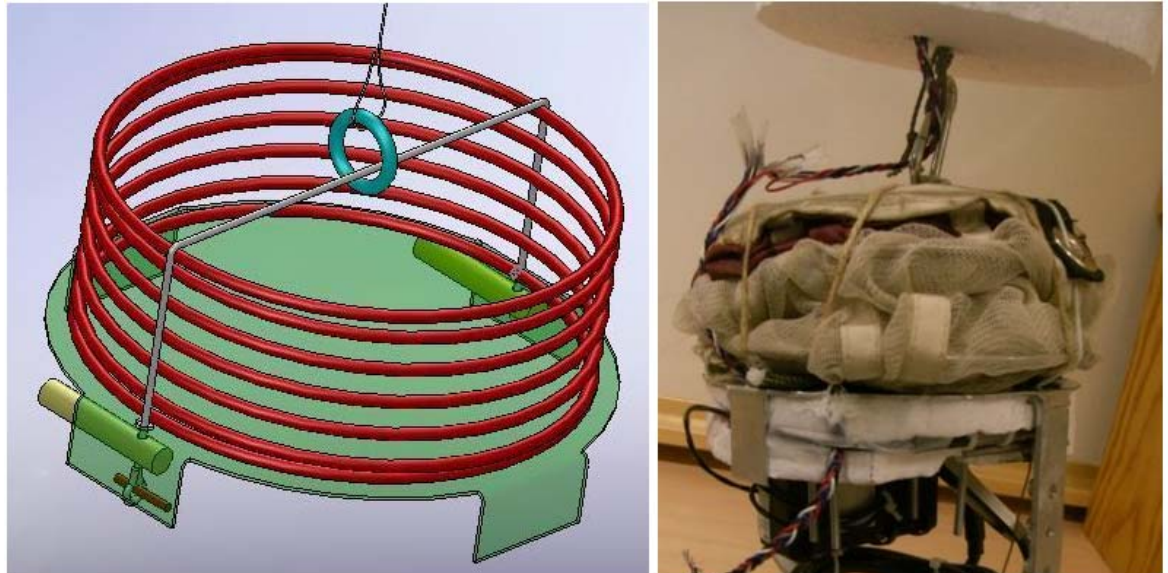


Figure 3.30, Figure 3.31 and Figure 3.32. The parachute is held down via the high strength line that is provided via CYPRES. This line has two loops pre spliced to ensure that the join maintains 100 % of the strength. This line is placed over the parachute and the loops are fed through the holes on the side of the beam and through the Release Unit (shown in Figure 3.32). The loop then has a steel pin inserted through it to keep the line in place. This process is also mirrored on the other side of the parachute.

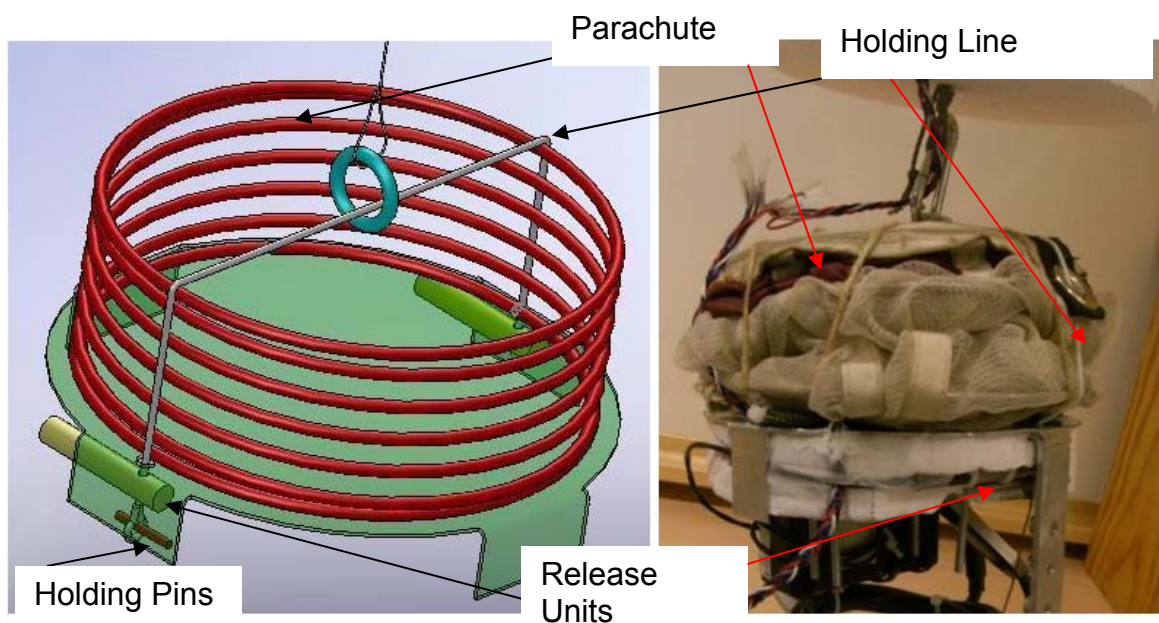


Figure 3.30: CAD Model of Parachute Mechanism

How the parachute is deployed is via the CYPRES unit sending a signal to the Release Units 'cutters' which will then cut the Holding Line. The Holding Line will become loose and the parachute will pull away from the parachute unit, letting the parachute down.

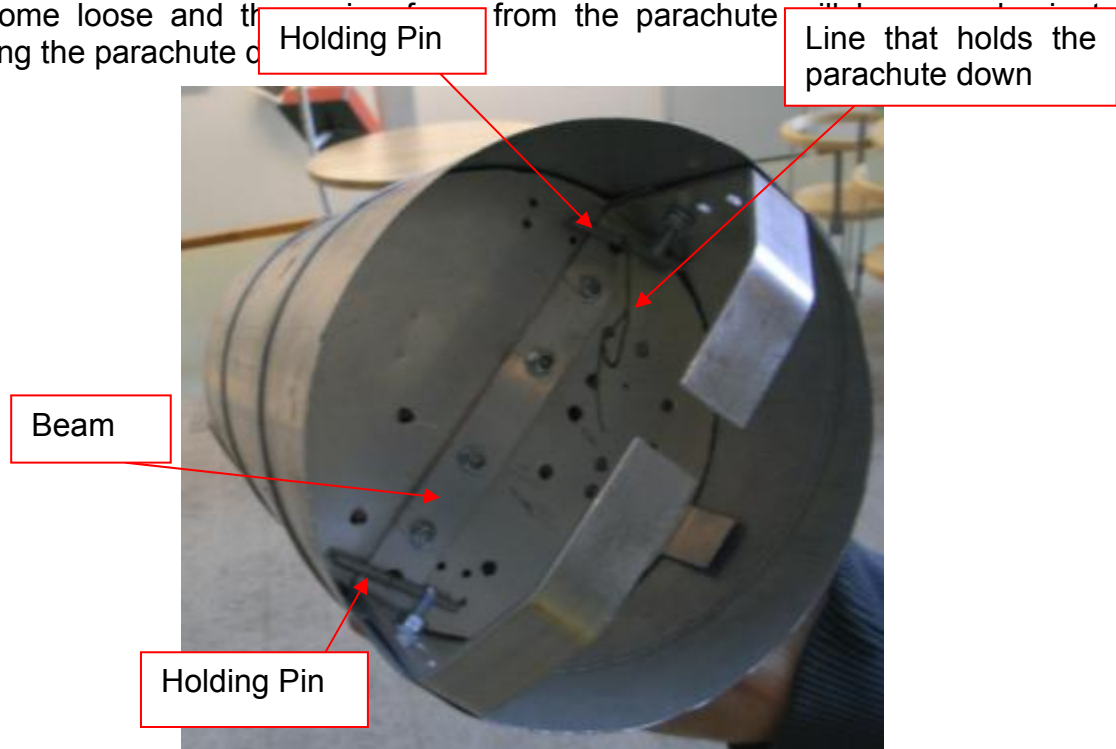


Figure 3.31: The Rear View Through the Nose Cone Position of the Parachute Deployment Mechanism

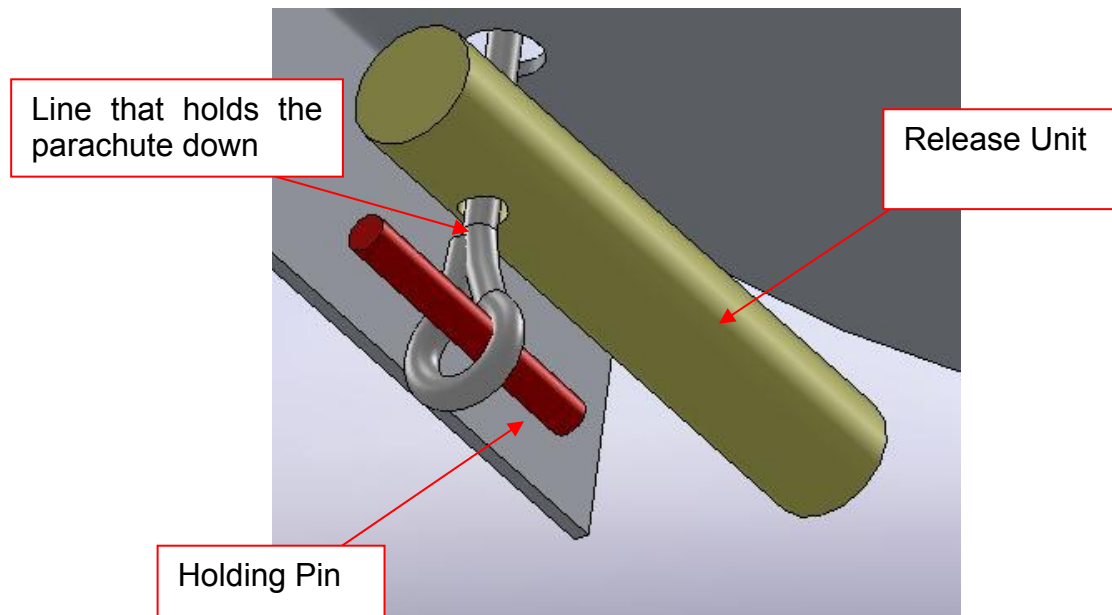


Figure 3.32: The Lock Pin for the Parachute Deployment Mechanism

The Parachute Release Mechanism

The parachute release mechanism is the Military CYPRES unit which consists of the

- Processing unit
- The Control unit, and
- The release unit (the cutter)



Figure 3.33: The Control Unit



Figure 3.34: The Release Unit

This unit is a fully contained device which triggers the release of a parachute when in free fall at a low altitude. How this works is through the use of the processing unit to measure the velocity and air pressure surrounding the unit. If velocity is higher than the activation velocity, along with the altitude being lower than the activation altitude, the release unit will close the blade and cut anything that is placed inside it. The activation settings are stated in the table below.

Activation Levels	
Velocity	35 m/s
Altitude	300 m

Table 14: The Activation Levels for the CYPRES Unit

The control unit is used to set the initial pressure for zero altitude. Thus the control unit must be easily accessible during the takeoff phase of the BEXUS campaign and is part of the prelaunch checklist. The CYPRES unit, once turned on, will turn itself off again after 14 hours. This should not be a problem for BEXUS but the unit must be switched on just before a launch is being conducted. For further information about the CYPRES unit please refer to the user manual (33).



3.6 Thermal Design

The extreme cold of the Stratosphere necessitates thermal insulation in order for the electrical components to remain within operational limits. Thermal control in this project incorporates both passive and active elements. Thermal control is critical to satisfying requirement Req.O.2. As such, a thermal analysis was conducted to determine both how to optimise the thermal design and the operational lifetime of the reel.SMRT system.

The reel.SMRT system is designed for flight at an altitude of between 25 and 35 km. The temperature differs with height but the lowest temperature the balloon is likely to encounter is 210 K. The ground temperature will be between 250 K and 270 K.

The MAIN Payload and FISH each present unique thermal design challenges. The MAIN Payload must be of sufficient temperature for the electronics to function, whilst not overheating the motors in this low-pressure low-convection environment. Conversely, the FISH must insulate the internal components such that the sensors and the electronics are stable and within operation ranges, whilst constrained in mass and volume.

In this section, the preliminary thermal designs to address these challenges to the MAIN Payload and the FISH are presented.

3.6.1 MAIN Payload

The MAIN Payload poses many challenges in the thermal aspects of the design. It is impossible in practice to be able to fully analyse the thermal processes involved in the MAIN Payload, and hence, the present section will outline some of the challenges and solutions. To start the analysis, the heat sources and sinks have to be identified. The most obvious heat sources are the motors; these include two brushless DC motors and one servo-motor. It is first noted that the servo-motor is only operating for a very short period of time and therefore, its heat generation may be essentially neglected. The DC motors, however, will reject a large amount of heat during their operations which can extend up to 0.5 duty cycle over five minutes or even up to an almost full duty cycle during the slow reeling down of the FISH payload. The electro-mechanical efficiency of motors can be estimated with good confidence to 50 %, including the gear-head losses. Overall, for power outputs of 30 W for each motor, the estimated heat rejection from the losses in the motors is of about 30 W per motor. Note that under no circumstances do the motors operate at the same time. This results in a total heat rejection of 30 W for all electric machinery, possibly up to a full duty cycle.

The second main heat source is the Lithium battery pack, which will typically have an efficiency of no less than 90 % (7). For this application, the operating power,

under normal conditions, can be estimated to less than 80 W. This leads to a heat production from the batteries of at most 8 W. Finally, with the addition of the electronics components and other frictional losses, the overall heat production over normal operation should be no more than 45 W.

The heat rejection is through the radiation and conduction from the inside components to the inside of the insulation casing and then through radiation into the atmosphere. It is very difficult to estimate the heat loss, and hence, the thermal strategy is formulated with the assumption that the heat rejection can be brought to a minimum with proper insulation.

Table 15 presents the thermal requirements for the various components in the MAIN Payload. It may be observed that the temperature ranges are quite permissive. Some electronics are preferred to be kept at a constant temperature above the freezing point, especially for the present selected brushless motor controllers. All other mechanical components are permitted to be kept in a temperature range of -20 °C to 50 °C.

Selected Components	Temperature (°C)		Heat Generation (W)	Comments
	Min	Max		
MAIN				
Reel Motor	-10	40	30	Around 0.5 Duty cycle over 5 min Up to full duty cycle Does not operate with Line Guide Motor Investigate magnetic losses and heat radiation properties of the permanent magnet rotor
Line Guide Motor	0	50	30	Around 0.5 Duty cycle over 5 min Up to full duty cycle Does not operate with Reel Motor Investigate magnetic losses and heat radiation properties of the permanent magnet rotor
Servo Motor	-20	60	~ 20	Negligible operating period
Batteries	-20	85	8	Possible destructive test required
Electronics - PCB 1	-40	85	< 1	Continuous operation
Electronics - PCB 2	-40	85	< 1	Continuous operation
Sleeve Bearing	-30	85	< 2	Verify Thermal Compatibility
Reel	N/A	N/A	~ 5	Testing Required ASAP

Table 15 Thermal Data for the MAIN Payload.

The thermal strategy formulated is based on minimizing the power consumption of any required heating elements. In order to achieve this goal, the insulation will be made as good as possible such that no heat flows out of the MAIN Payload.



During the pre-experiment phase, the temperature of mechanical components can be kept to no less than -20 °C by means of heating pads. For the flight, the heating pads are removed, rendered unaffactive, and active heating elements will ensure thermal regulation of critical components. Then, during the experiment phase, the heating elements will be turned off and the heat generated from the aforementioned heat sources will slowly heat the mechanical components of the MAIN Payload through conduction. The heat capacity of all components, based on the assumption of negligible heat flux to the surrounding environment, shall be sufficient to keep the overall temperature of the mechanical components below 50 °C during the whole experiment. The following rough calculation gives the time required to heat the components from -20 °C to 50 °C.

$$C_{th} > c_{al} \cdot m_{al} + c_{st} \cdot m_{st} \quad 1$$

$$C_{th} > 0.896 \frac{J}{g^{\circ}C} \cdot 3270 g + 0.46 \frac{J}{g^{\circ}C} \cdot 4400 g = 4954 \frac{J}{^{\circ}C} \quad 2$$

$$\dot{Q}_{gen} \cdot \Delta t = C_{th} \cdot \Delta T > 4954 \frac{J}{^{\circ}C} \cdot (50^{\circ}C + 20^{\circ}C) \quad 3$$

$$\Delta t > \frac{346780 J}{45 W} = 7706 s = 128 min = 2.14 hrs \quad 4$$

The above equations show that it should be possible to operate the experiment on full duty cycle for the required time without overheating the components of the MAIN Payload, even in the absence of any heat rejection to the outside environment. In practice, the conduction of the heat throughout the mechanical components will not be instantaneous, although aluminium offers great thermal conductivity, and hence, the temperature will not be uniform. This problem will be counteracted by measures to facilitate conduction around the heat source and improving thermal interfaces between components. The heat loss, although reduced to a minimum, will favour the extension of the time before overheating the mechanical components of the MAIN Payload. Additionally, temperature sensors were installed inside the MAIN Payload to assess the thermal balance and ensure that the heat sources can be shutdown in time.

During the campaign week, the final implementation of the thermal regulation system was implemented and the flight data showed a very satisfactory performance. Several critical items were directly thermally regulated in closed-loop. These include: the battery pack, maintained at 5 °C; the motor controllers, maintained at 10°C; the micro-controller board, maintained above 0°C; the reel maintained above -10°C; and the line-guide safety brake, maintained above -5°C. These temperatures were chosen by examination of the manufacturers recommendations. Temperature sensors were also placed on the motors to monitor them, although no direct thermal regulation was possible due to limited number of heaters. Figure 3.35 shows an example of the thermal regulation system for the motor controllers.

Additionally, to prevent cooling on the launch pad, a Styrofoam plug and 6 chemical heaters were used within the MAIN Payload.

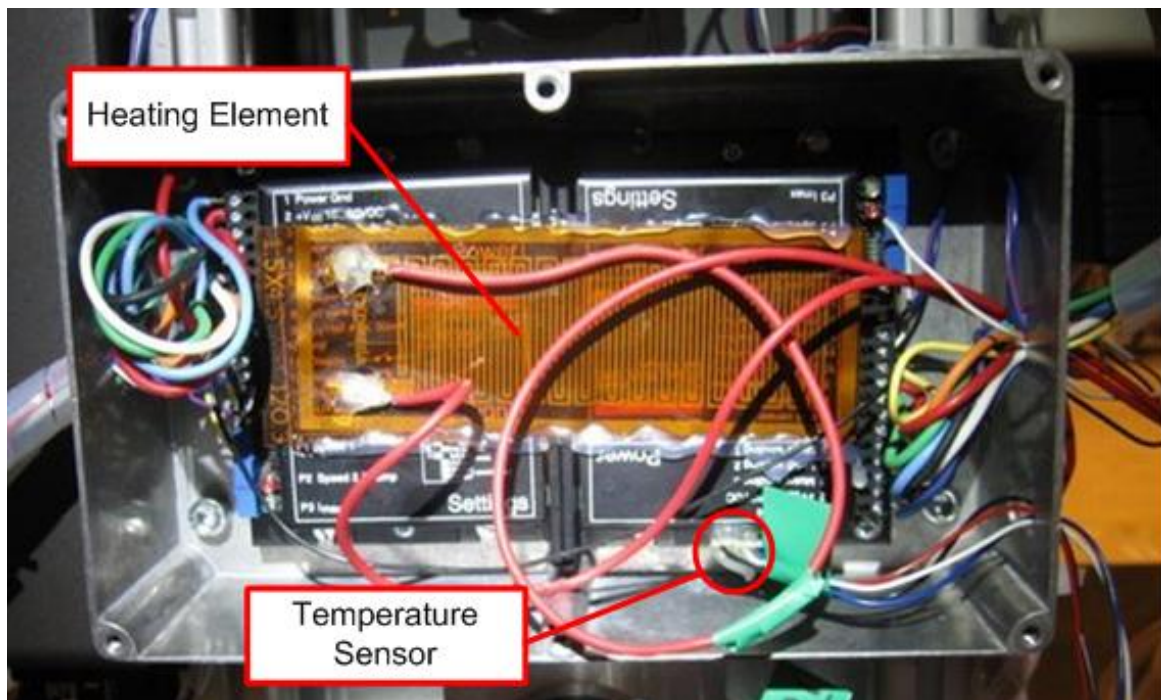


Figure 3.35 Open view of the as-built motor controller box, showing an example of thermal regulation hardware used.

3.6.2 FISH Payload

The thermal requirements of the FISH are dictated by the operating temperatures of the electrical components shown in Table 16. The optimal temperature for the complete FISH is 20°C but due to this high value, further analysis shall be conducted as to whether this is viable.

FISH ELECTRONICS	min (°C)	max (°C)
Accelerometer	-55	125
ADR445 B grade	-40	125
TMP275	-40	125
LIS3L02AQ3	-40	85
ADC1253	-40	85
Zigbee	-40	80
Cypres	-30	62
Batteries	-60	80

Table 16: Thermal parameters for the FISH components

There are two main areas of thermal interest on the FISH

1. Thermal environment of PCB,
2. Thermal environment of radio

Thermal Case 1

The PBC environment uses both a passive and active forms of heating as shown in Table 17. This includes that the electrical systems are surrounded by 15 mm-25mm of low density Styrofoam that that the properties shown in Table 17. The area that all electrical components are housed is approximately 475,300 mm³ which is very small thus less power is used to maintain a constant temperature around the electrical devices.

Properties		Reference
Specific Heat	1.3 kJ/kg.K	(34)
Thermal Conductivity	0.08 W/m.K	(34)

Table 17: Properties of Styrofoam

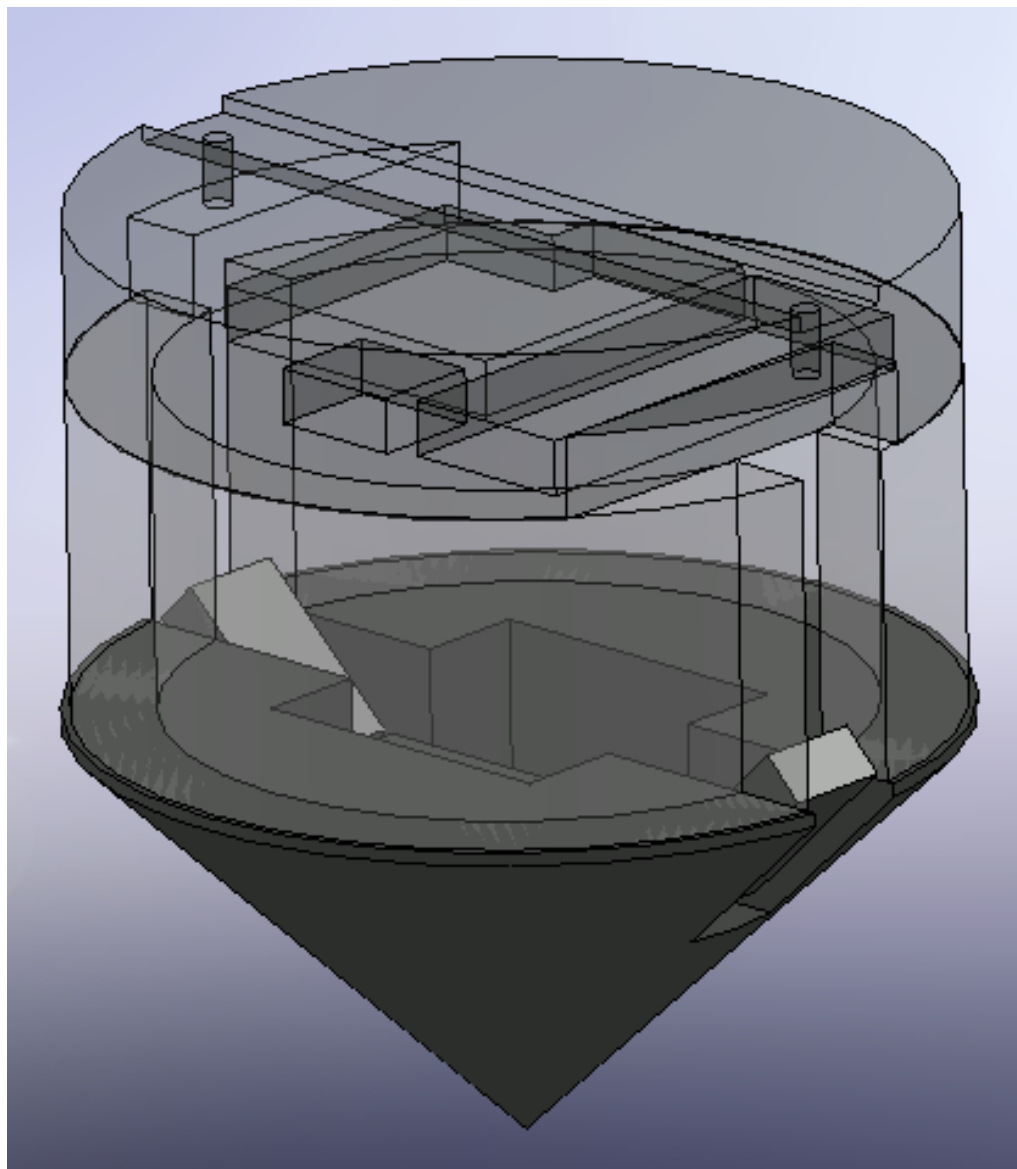


Figure 3.36: FISH's Main insulation

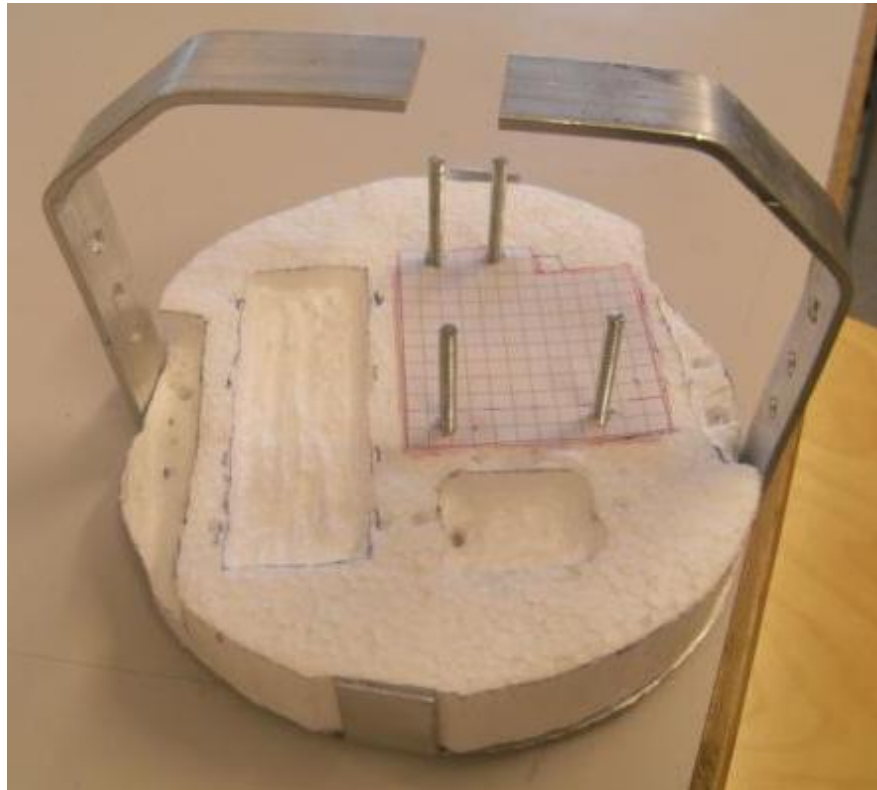


Figure 3.37: The insulation attached to the Base plate

Thermal Case 2

For the Radio thermal environment the minimum of 30 mm thick insulation is used to surround the radio unit to make sure the temperature is in the correct limits. There will be no active heating involved in this area but there will be small amount created by the radio itself. Figure 3.38 shows the configuration of this insulation.

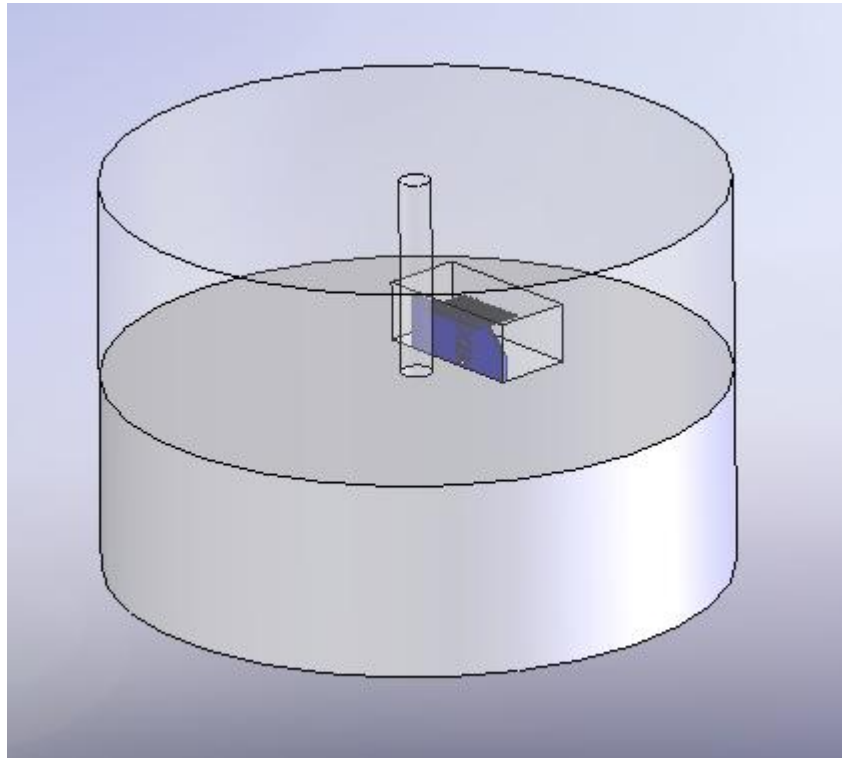


Figure 3.38: Thermal Insulation of Top

This insulation has a hollow box in the middle of it, through which the main line is fed through. This will open up the inside of the insulation to the outside temperature. Since the hold is fairly small the amount of heat that is lost will be negligible due to the atmospheric density.

During the launch campaign, the FISH was not left on the launch pad but rather was taken out and attached to the line at the time of last possible access, to optimise its thermal performance.



3.7 Software Design

The reel.SMRT experiment has complex control and data storage processes. To control the entire experiment and to be able to store the sensor data at the same time whilst having enough processing power remaining to check the whole setup for malfunctions, a thorough software architecture is necessary.

The microcontrollers (NXP lpc2368) were selected so that they can provide the necessary processing power during all times of the flight. This microcontroller runs at 70 MHz and provides diverse inputs (analogue-to-digital converter, UART, SPI, I²C, secure digital interface) to easily connect all sensors without the need of additional external converters.

The first microcontroller is located on the FISH, with the second on the MAIN Payload. In Figure 3.39 the connection of the sensors and the communication links between the FISH and the MAIN Payload is displayed.

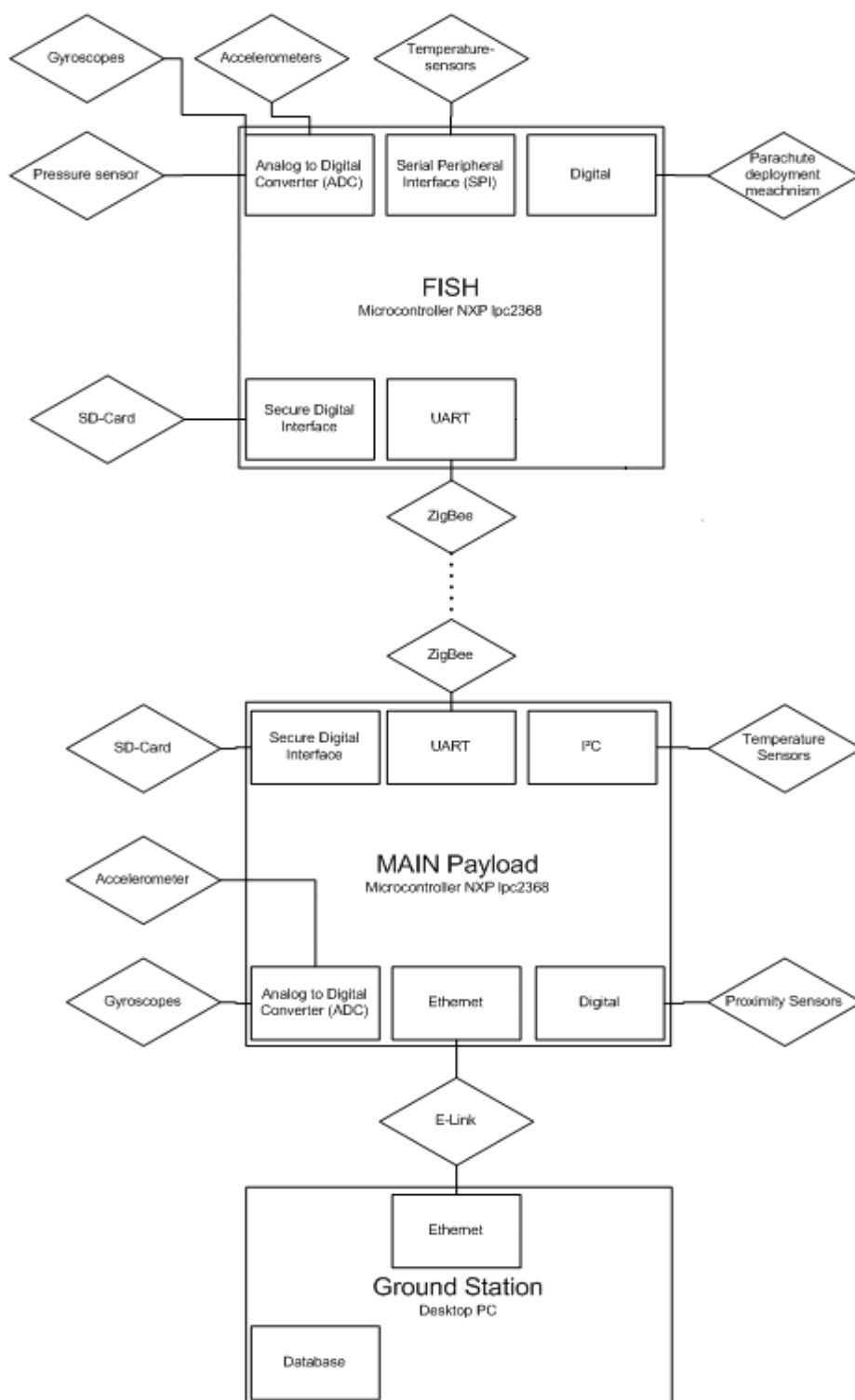


Figure 3.39 FISH, MAIN Payload and Ground Station Software System Design



3.7.1 Operating System

During the execution of experiments several tasks have to be processed at the same time. These tasks include:

- Control of the free-fall (open bail, close bail)
- Control the system health (sensor malfunction check)
- Store sensor data (on local SD-Card)
- Transfer sensor data to ground station

For this reason a real-time operating system (RTOS) shall be employed. The advantage of choosing a RTOS is in its deterministic behaviour. This means that the maximum execution time of all instructions is known. It also allows writing functions that will execute in a pre-calculated amount of time.

During the free-fall experiment the time between the opening of the bail (beginning of the free-fall) and its closing (end of free-fall, beginning of braking) is very critical. If a real-time operating system is used, the internal task scheduler allows a guaranteed maximum time between opening and closing, even if other parallel tasks are running at the same time (like a large data transfer).

Normally, real-time operating systems are very costly because of the complicated design of a deterministic task scheduler and the necessary certification process.

However, there exist uncertified free RTOS. One of them is FreeRTOS [24]. There exist ports to several different microcontrollers, including the one used in this project.

One disadvantage is that real-time scheduling always reduces the processing power of the microcontroller. For that reason the microcontroller has been selected with margins for processing power.

3.7.2 Programming Language

When using FreeRTOS the list of supported programming languages is rather short. The most frequently used language for the lpc2368 is the C Programming Language. For this language a variety of Integrated Development Environments (IDE) exist, simplifying the development process. The project chooses Eclipse as an IDE for developing the software.

The program for both the FISH and the MAIN Payload is written in C. It will consist of different kinds of tasks that run in parallel (pre-emptive multitasking):

3.7.3 Tasks

The control of the entire experiment is realized using two microcontrollers onboard the balloon. Since there are many functions that have to be executed independently, they were split up into tasks. Tasks are subparts of a program that can run in parallel without interfering with other tasks. It is therefore possible for



example to control the bail opening servos ("Task 1") and transfer sensor data to the ground station ("Task 2") simultaneously.

3.7.3.1 Atomic tasks

This type of task consists of one singular action (e.g. "READ_TEMP_SENSOR_1"). They can be executed in any order independent of any other tasks that might be executed at the same time.

3.7.3.2 Composed tasks

Composed tasks consist of a set of atomic tasks and therefore execute a sequence of tasks. Some composed tasks cannot be executed simultaneously. An example composed task is for example "OPEN_BAIL". It consists of the atomic tasks:

- MOVE_REEL_TO_BAIL_OPENING_POSITION
- CHECK_REEL_SPEED and
- OPEN_BAIL_100_DEG

3.7.3.3 Control tasks

The most difficult tasks implemented in the reel.SMRT software are control tasks. They consist of a sequence of composed tasks that control certain behaviour of the experiment. A control task is for example responsible for detecting a malfunction in the reel brake. It consists of the following sequence of composed tasks:

- If "BAIL_CLOSED" and "REEL_SPEED = 0"
- If "FISH_RELATIVE_ALTITUDE_CHANGE = 0"
- = no_malfunction

These tasks do not necessarily have to be one capsulated task. Single direction operations (like reading a sensor value) can be executed in an additional task. The sensor value is then stored in a global variable.

3.7.4 **Microcontroller Program Structure**

The program structure of FreeRTOS is divided into different task. Tasks and their interaction have been implemented for the reel.SMRT experiment and are displayed in Figure 3.40 and Figure 3.41.

In the reel.SMRT system, the data task acquires sensors data every interval time and has the highest priority. Then the data task constructs the packet and adds it to send buffer waiting for uIP task to send it over TCP network. uIP task reads the data from the send buffer as well as from SD card when the send buffer is empty. uIP task also receive the command from ground station and send it to control task to handle it. Control task receives command and process it e.g. turning the reel

```

graph TD
    Sensors([Sensors]) --> DT[Data Task]
    DT -- "Command from GS" --> CT[Control Task]
    CT -- "payload data packet" --> DT
    CT -- "Command result" --> AM[Add data to send buffer method]
    AM -- "FISH data packet" --> FT[FISH Task<br/>(zigbee handle)]
    FT -- "Give semaphore" --> AM
    FT -- "zigbee" --> ZigbeeOut((zigbee))
    FT <--> |"Send command to FISH"| CT
    CT <--> |"Reply to command"| FT
    CT -- "Change mode" --> DT
    DT --> UT[uIP Task<br/>(TCP network)]
    UT --> ELink[E-Link]
    UT <--> B[Buffer<br/>(RAM)]
    UT <--> SD[SD Card]
    B <--> SD
    SD --> AM
    RS232[RS232 ISR] -- "Character come from zigbee" --> AM
    RS232 -- "Give semaphore" --> FT
  
```

The diagram illustrates the FISH system architecture. It features four main tasks: Data Task, Control Task, FISH Task (zigbee handle), and uIP Task (TCP network). The Data Task receives input from Sensors and sends a 'Command from GS' to the Control Task. The Control Task sends a 'payload data packet' back to the Data Task and a 'Command result' to the 'Add data to send buffer method' block. This block then sends a 'FISH data packet' to the FISH Task. The FISH Task sends a 'Give semaphore' signal back to the 'Add data to send buffer method' block. The FISH Task also handles 'zigbee' communication. The Control Task sends a 'Change mode' signal to the Data Task and has bidirectional communication with the FISH Task, labeled 'Send command to FISH' and 'Reply to command'. The Data Task sends data to the uIP Task, which then connects to an 'E-Link'. The uIP Task is connected to a 'Buffer (RAM)' and an 'SD Card', which both feed into the 'Add data to send buffer method' block. An 'RS232 ISR' block receives 'Character come from zigbee' and sends a 'Give semaphore' signal to the FISH Task.

FISH has similar tasks to the reel.SMRT payload but the uIP task has been placed by send task. The data task and control task in FISH operate in the same way as in the reel.SMRT payload. The data from reel.SMRT payload are received via RS232 and activate the MAIN Payload task via semaphore.

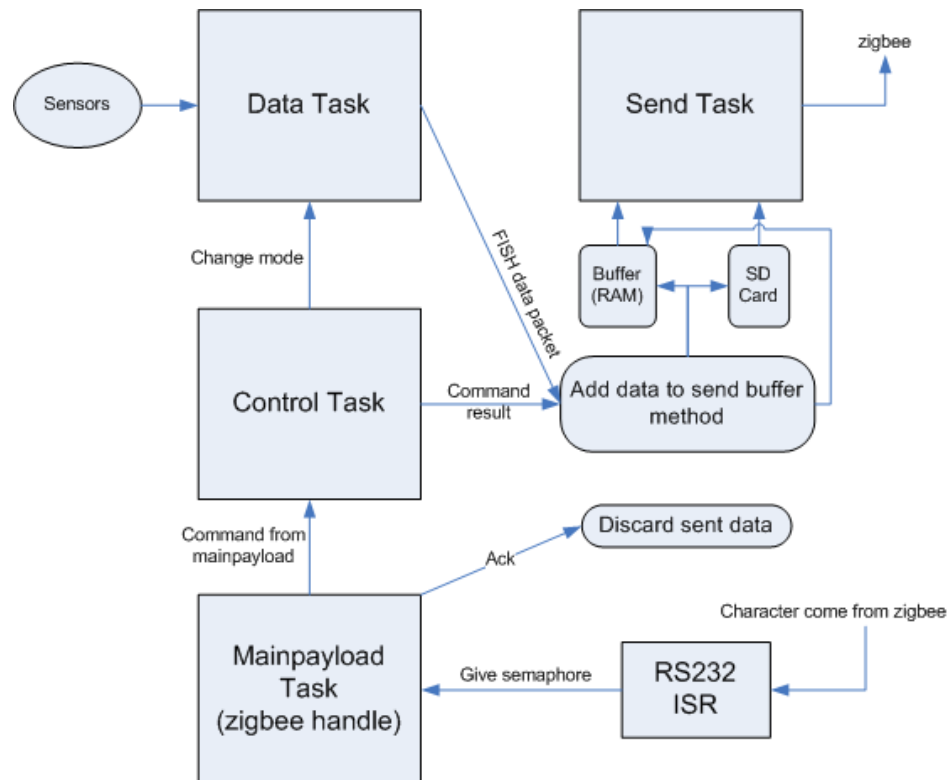


Figure 3.41 FreeRTOS Tasks and Their Interaction implemented in the FISH

3.7.5 Ground Station

The ground station mainly consists of graphical user interface (GUI) that helps the ground crew to supervise the performance of the experiment during the flight. If sensor data is downloaded during the flight, the values are displayed in graphs so that unexpected behaviour can be identified very quickly. The graph feature has not been implemented due to lack of time.

During the mission it is necessary to communicate with the balloon pilot, because some special settings have to be made before the FISH can be dropped. This mainly includes deactivation of the balloon cutting mechanism, which is automatically triggered if a high acceleration in z-direction is detected. When the FISH is released, it is possible that this triggers the cutting mechanism. In addition, drops are only allowed when the balloon is afloat over uninhabited areas and the reel.SMRT operator has approval.

The experiment operator therefore needs an explicit clearance for each drop or slow reel operation. The ground station also supports issuing telecommands to the balloon to be able to work problems that may occur during the execution of the experiments. Those telecommands could be, for instance, as follows:

- OPEN_BAIL_3sec or



- SLOW_REEL_2sec or
- CLOSE_BAIL

Furthermore, sensor status data is also available. Therefore it is possible at any time to detect upcoming irregularities and to respond to them swiftly. The user interface of the ground station is shown in Figure 3.42.

The ground station software shall be operated on a standard Personal Computer (PC). The data from the E-Link system will be fed into the computer via the standard Ethernet interface of the PC.

The control of the experiment during the flight will be done by a member of the reel.SMRT team (“experiment operator”). This person will be trained to operate the experiment and initiate contingency commands in case failures occur. For that reason a simulated countdown is planned to take place one day before the launch.

The control of the entire BEXUS balloon is done by trained personnel from ESRANGE. This person is called the “balloon pilot”.

In addition to the visualization of the experiment parameters, all down-streamed sensor data is stored in text files on the hard drive of the PC. This allows easy data analysis beginning directly by the end of experiment even before the landing of the gondola.

The maximum size of the data files will be reasonably small. Even if 20 slow reel experiments are performed during the flight (with about 10 sec * 288 kBit/sec) the maximum size will not reach 12 MBytes. Therefore it is not necessary to use a high performance PC.

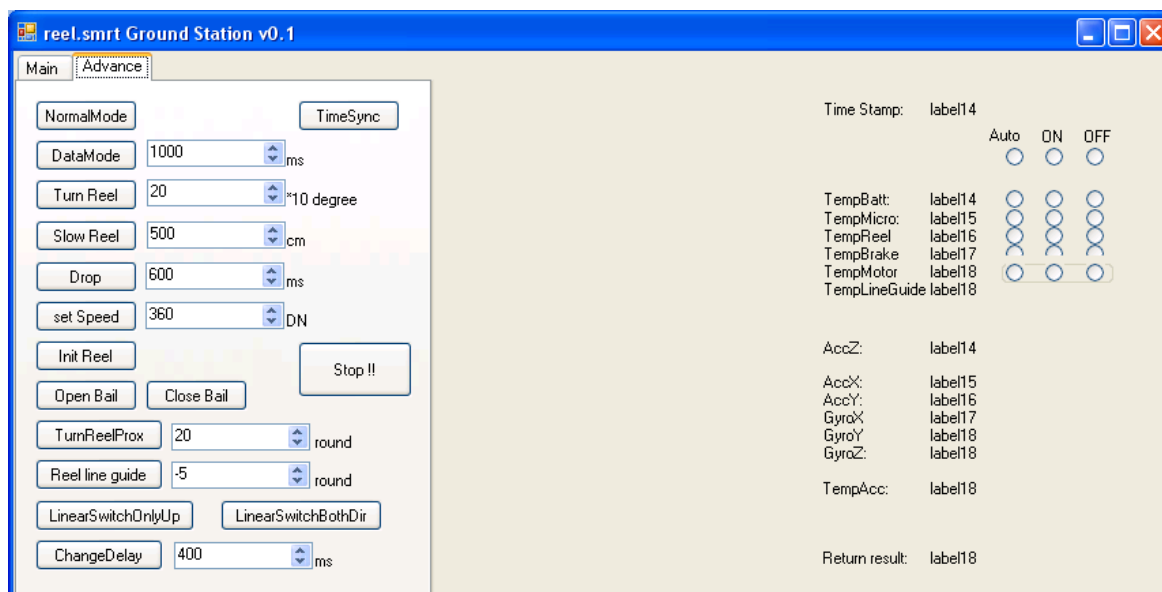


Figure 3.43 Ground station program user interface.



Figure 3.44 The Ground Station in operation during the flight

3.7.6 Safety

Several functions are implemented to avoid any danger from the experiment. Some of the safety functions are:

- Battery temperature detection (heating perform for maintain the temperature)
- Real-time operating system (deterministic behaviour of the reel control)



3.8 Experiment Electrical System and Data Management

The Electrical Subsystem consists of two key segments: the MAIN Payload and FISH electronics, which are electrically isolated from one another. The MAIN Payload electronics provide and distribute power to the MAIN Payload, to ensure correct motor and sensor operations. The design consists of three PCBs to achieve these tasks. The FISH electronics design consists of a small PCB containing the key sensor and control equipment required to generate the store the desired data. The systems interface with the Xbee Pro 868 modules, through which data from the FISH is transferred to the MAIN Payload for duplicate storage and transmission to the ground station.

3.8.1 MAIN Payload Power System

The MAIN Payload shall utilise five 22.2V 2200 mAh Power Polymer Li-Ion packs. These are to be connected in parallel to achieve a nominal capacity of 6600mAh for main motor and 4400 mAh for the emergency motor. The capacity of the batteries has at least a 25% margin; however, the precise number is to be determined by thermal analysis, specifically, the power needed to keep the whole subsystem above 0 degree.

AA Portable Power Corp - High Power Polymer Li-Ion Pack - 22.2v 2200mAh (24.42Wh, 40A rated)

These battery packs were selected because they are extremely light and provide high current capabilities.

The batteries were replaced during the campaign by two packs of batteries. Those batteries were of the same properties (Li-ion Pack 22.2V) but the capacity was 4600mAh and 5400mAh. These packs were used in similar redundant topology (3+2 became 1+1). The replacement was caused by deep discharge during final tests. Although the original batteries may have been still usable team did not want to jeopardize other experiments by using unstable batteries.

3.8.2 Power Budget for MAIN Payload

The most significant energy consumption comes from the motors, predominantly the reel and line guide motors. The reel motor is to be used for 20 drops each lasting 120 seconds based on specifications from the mechanical subsystem. The motor is to consume 50 W rated at 24 V.

The battery capacity could be sufficient for a minimum 30 drops. The amount of drops is dependent on the power distribution within the power subsystem, since two different sets of batteries are shared amongst the power supply for all components but only one set is used for the motors (one for the emergency motor and one for the main one). In case that the power supply for the system is to be provided mainly from the battery set used for the emergency motor; this is to enable more capacity for the main motor and prolong the number of drops. The capacity of all batteries is monitored by the ground station, and hence the decision regarding when the experiment is to be stopped could be done after each drop based on the available capacity.

The redundancy in the power supply is achieved by combining three battery packs for the main motor and two battery packs for the emergency motor. In case of the failure of one battery pack, both motors could be still usable. The structure of the power supply is depicted in Figure 3.45.

During the campaign battery 1 to 3 were replaced by one battery of the nominal capacity of 5400mAh, whereas battery 4 to 5 were replaced by one battery pack of the nominal capacity of 4600mAh.

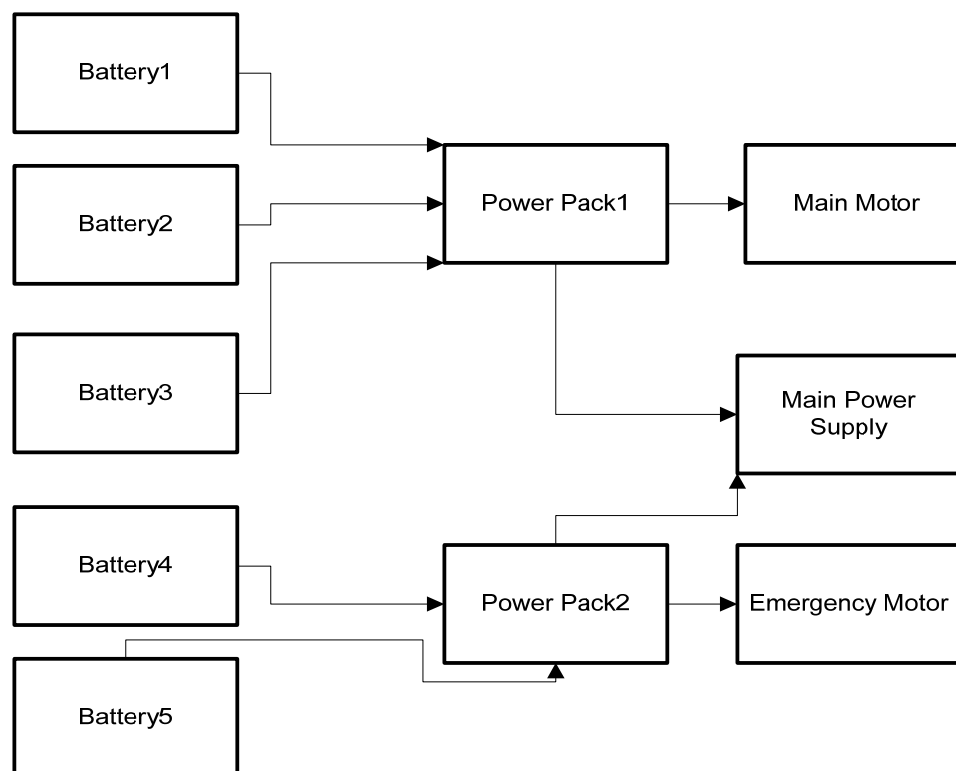


Figure 3.45 Structure of the Power Supply



3.8.3 MAIN Payload Electronic Design

In this section, the design of the MAIN Payload is detailed along with a single point failure analysis.

The MAIN Payload electronic design consists of three PCBs of dimension 104 mm x 134 mm (microcontroller), 171 mm x 152 mm (Power Supply Distribution) and 177 mm x 107 mm (Motion Control).

The IP Camera is not included in this analysis. This is because the camera is to be powered up from a separate battery pack consisting of three Li-Ion pieces each rated at 3.7 V with the nominal capacity of 2300 mAh.

Although originally proposed in the CDR, following a careful consideration of the advantages and disadvantages of using fuses it was decided that they shall no longer be used in the reel.SMART MAIN Payload design. The main reason is that the controllers for the motors do have a current limit and all dc/dc converted are current limited also. These features effectively minimise the potential risk of high current flow and hence over-heating and explosions.

3.8.3.1 MAIN Payload Power Budget

The detailed power budget could be found in Sections 3.3.8 with the associated calculations. The calculations show that the maximum amount of drops which shall be able to be achieved is 30. This is based on the assumption that only 75 % of full battery capacity will be available in the worst case power distribution scenario. The power budget has a 25% of margin since we are going to use heaters to keep the batteries above zero degrees, which means that we will use almost 100% capacity.

After using the new set of batteries the calculations would not change dramatically since the difference in capacity is only 1100mAh which is 11% of the total capacity used.

3.8.3.2 Reel motor, Line Guide Motor (Emergency Motor)

The motors are rated at 24 V and 2.5 A continuous current. In order to deliver sufficient stall torque (400 % nominal one), the peak current has to be 10 A. This was taken into account and the power system circuitry was designed for handling 16 A peak current. The limit of the torque is because the current brushless controller has the maximal current of 10 A (initially the controller which was designed was capable of delivering 15 A).

Both motors are connected to the main power subsystem by two independent cables each connected to Hirschman GDM 3016 connector, where two pins are connected together in order to reduce the possible connector failure.



3.8.3.3 RC Servo Motors

RC (Radio Controlled) Servo Motors are widely used in model of planes. In this application these servos will be controlled by sending a pulse with a length corresponding to the angular displacement CPM (Code Pulse Modulation). The control will be done not wirelessly but via wire.

The RC Servo Motors were selected for the particular task of flipping the bail and hence, initiating the drop. The electrical subsystem design involves the handling of 1 A of continuous current for servos rated at 10 V. The electrical subsystem includes two such servos, for redundancy purposes. For more information on the selection of these motors, refer to the mechanical section of this report.

During the testing, it was found that the RC Servo Motors were not powerful enough. This led to the change in mechanical design. Those servos were replaced by more powerful ones with nominal voltage of 18V and nominal current of 1A. The PCB did not have to be changed since the original regulators (10V) had the same footprint as the new ones (18V).

3.8.3.4 Battery Pack

A High Power Polymer Li-Ion Pack of 22.2 V and 2200 mAh was selected as a primary source of energy on the MAIN Payload. In order to keep the weight as low as possible and also to deliver the stall current for the reel motor when engaging the brake, the selection was made for this power demand. This power supply is able to deliver up to 40 A, which is well above required value; however, in terms of weight (340g per piece) these batteries provide excellent option for the experiment.

For more information regarding batteries and their redundancy see Section .

3.8.3.5 Power Supply

The power subsystem consists of following parts:

a) *DC/dc converters*

i. *24/5*

This adjustable isolated dc/dc converter is to provide main power supply for the 5 V devices and for 5/3.3 V linear regulator.

This regulator is doubled to reduce the single point of failure. Both dc/dc converters are equipped with EMC filters.

ii. *24/+12*

The aim of these dc/dc converters is to provide $\pm 12V$ for the primary and secondary side. This is used for isolation amplifiers to isolate primary and secondary side.

Both dc/dc converters are doubled and all equipped are with EMC filters.



iii. 24/10

These linear regulators are used to provide power for the RC servos. The power which has to be dissipated in these regulators is $(24 - 10) \times 1 = 14W$; however; the servos are to be for only a minimum 10 times during the mission and every servo will be used only for one second (flipping the bail and return).

The stand-by dissipation is defined by quiescent current which is $(24-10) \times 0.0065 = 100$ mW. If the power cannot be dissipated these regulators have to be replaced by switching ones TO-220 compatible.

These regulators were replaced by 24/18. Since the voltage drop got lower $(24-18=6V)$, the power dissipation also went down.

iv. 5/3.3V

This linear adjustable regulator is to power the 3.3 V devices. This regulator is doubled. The power dissipation across them is to be $0.25 \times (5-3.3) = 425$ mW (Based on the power budget stating that up to 250 mA is needed for a 3.3 V system). Both regulators are to be equipped with heat sinks; however; if Power Supply Comprehensive Test show that the heat cannot dissipate, the thermo grease has to be added to connect heat sinks to the aluminium box.

b) Monitoring Circuit

The monitoring circuit is based on analogue multiplexer, optocouplers and an isolated amplifier. It monitors all batteries (five) and also both power sets. It uses simple voltage dividers to scale down the voltage to appropriate level (24V to 3.3V). The optocouplers isolate the primary and secondary side and address the multiplexer which switches the selected voltage to be measured by microcontroller through isolated operation amplifier which isolates primary and secondary side. It keeps the main power system isolated from the other circuitry. Hence, the interference due to the inductive load should be limited and measurement and reliability should be greatly improved. The isolation also greatly contribute to the safety aspect of the mission by keeping high voltage and low voltage devices on the separate ground.

The power supply is to be connected to other parts of the system by IP65 rated connectors Hirschman GDM3016. Every motor will use two separate connectors and wires in case of connector/wire failure. The power distribution (5 V, 3.3 V, ± 12 V) for other circuitry will also use two separate connectors (Cannon D-SUB connector) and wires. Please refer to the Appendix 3 to see the schematics and the components list



3.8.3.6 Microcontroller, Sensors

The box with microcontroller has several connectors:

- a) Power supplies (+5V,+3.3V,+12V primary side-CON1-4)
- b) Connector for programming (CON5)
- c) Connectors for infrared sensors (CON6)
- d) Connectors for hall sensors(CON7)
- e) Connector for optical encoders (CON8)
- f) Connector for temperature sensors(CON9)
- g) Connector for servo control(CON10)
- h) Connector for IMU unit (CON11,CON12)
- i) Connector for ZigBee (CON13)
- j) Connector for Ethernet (CON14)
- k) Connector for SD card (CON15,CON16)
- l) Brushless servo control (CON17)

The interface to the brushless controller (integrator, operation amplifier to convert 3.3V to 5V), the programming interface (rs-232 driver) and the 2.5V voltage reference for IMU unit is depicted in section 5.4.

The MAIN Payload is to be equipped with the inertial unit. This unit consists of three ADXRS300 gyroscopes and two two-axis accelerometers of type ADXL210. The analogue output values of these sensors shall be fed into a 16-Bit ADC (ADS8344). In addition, the internal temperature sensors of the gyroscopes can be read out (the accelerometers don't have an internal temperature sensor). Since the ADC only has eight inputs only one port is left for the temperature reading (three inputs for the gyros, four inputs for the accelerometers). To choose the temperature source a multiplexer is used (CD4067BE). For more information see appendix.

3.8.3.7 Microcontroller

The microcontroller used in the MAIN Payload is NXP lpc2368 and it is identical to the microcontroller in the FISH. This is a single chip 32 bit microcontroller, based on a 32 bit ARM7 CPU, which has: 512 kB flash, SPI, I²C, 10 bit ADC, and four UARTS, among many other peripherals. This makes it ideal for application to the reel.SMART system as it has plenty of ports and interfaces that will enable the system to be able to handle multiple sensors and be able to store the data as well as transmit it to the wireless module so it can be backed up and see the status of the mission in real time. For more information on the microcontroller please refer to Section 3.7. Due to the unanticipated interference between Ethernet driver and SD card (they could not work simultaneously), this board was replaced by evaluation board. For more information see following section.

3.8.3.8 Microcontroller, Modified evaluation board

Because of the original microcontroller PCB cannot provide full functionality during test. The evaluation board that has been used and tested during software development is used as the flight electronic. The power connectors and interface connectors have been added to the evaluation board to perform the experiment which can be seen from Figure 3.46. The prototyping board, Figure 3.47, is connected on the top of the modified evaluation board with the normal pin connector in Figure 3.48. The final configuration of the connection can be seen in Figure 3.49. The power connectors from the power supply electronic are connect the input power to the evaluation board and the on top prototyping board. Microcontroller peripheral connectors provide IO ports and connection to the prototyping board.

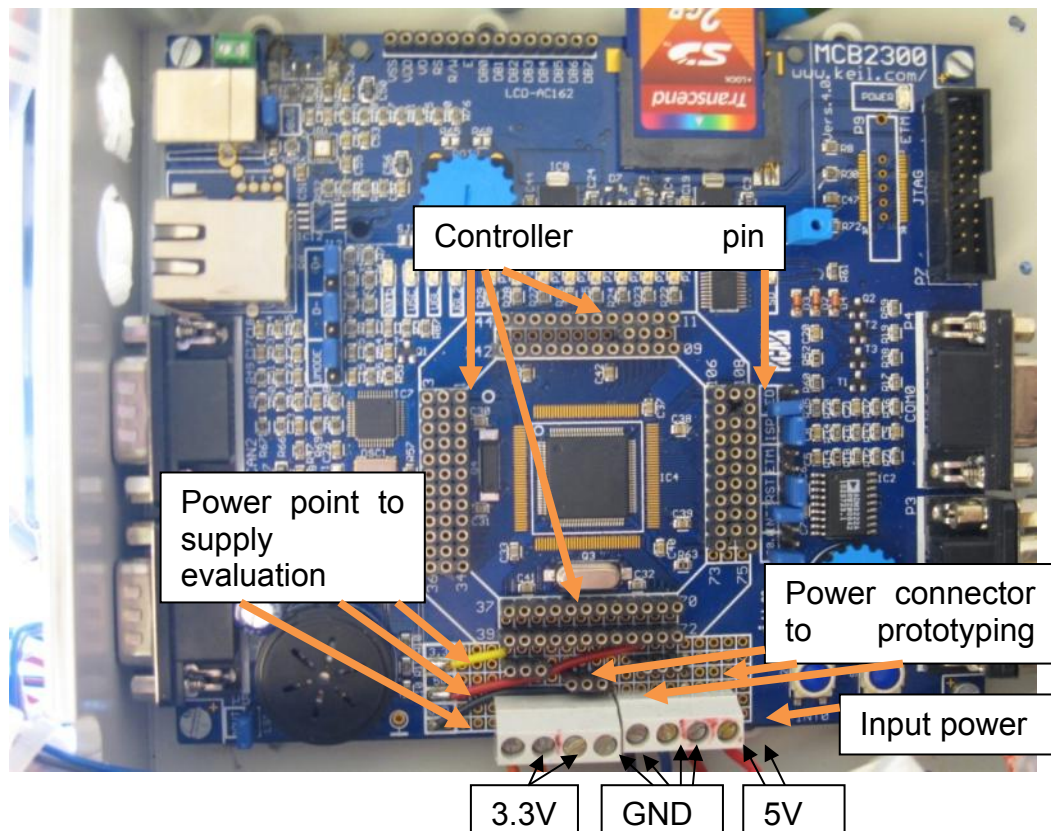


Figure 3.46 Modified Keil evaluation board

3.8.3.9 Microcontroller, on top prototyping board

The prototyping board provides the interface to experiment sensors and actuator (Figure 3.47). Table 18 shows connection to other experiment module from the on top prototyping board. The connections to other modules are connected by connectors which provide possibility to connect and disconnect easily. The flight configuration connection is shown in Figure 3.50. The schematic of connection

from the evaluation board is shown in Figure 3.51. The detail schematic and layout can be found in Appendix 3.

Table 18 Peripheral interface from on top prototyping board

Sensor/Actuator	Interface from microcontroller	Remark
Reel motor controller	- SPI via DAC, provide analogue output to the motor controller to control the velocity of the motor - 2 GPIO for enable and direction	
Line guide motor controller	- SPI via DAC chip, provide analogue output to the motor controller to control the velocity of the motor - 2 GPIO for enable and direction	
Servo for bail opening	- UART via RS-485 chip, provide 2 wire serial connections to the servo motor.	
Redundant servo for bail opening	- UART via RS-485 chip, provide 2 wire serial connections to the servo motor.	No use
Heater and Brake	- 6 GPIO for open and close power transistor	
Temperature sensor	- I2C provide 6 channel temperature measurement	Use only 5 channel because of one broken sensro
Linear actuator	- 2 GPIO for H-bridge power control - 1 analogue input for position feedback	Position feedback did not implement in the software
Zigbee	- UART interface	No use, use the COM1 connector directly from the evaluation board
Hall sensor reel	- 1 GPIO input	
Hall sensor line guide	- 2 GPIO input	Use only 1 channel

Proximity sensor	- 1 GPIO input via Schmitt trigger	
Big proximity sensor	- 1 analogue input	No use because of lack of test
Battery voltage measurement	- 3 GPIO for channel multiplexer - 1 analogue input for battery voltage measurement	No use because of lack of test

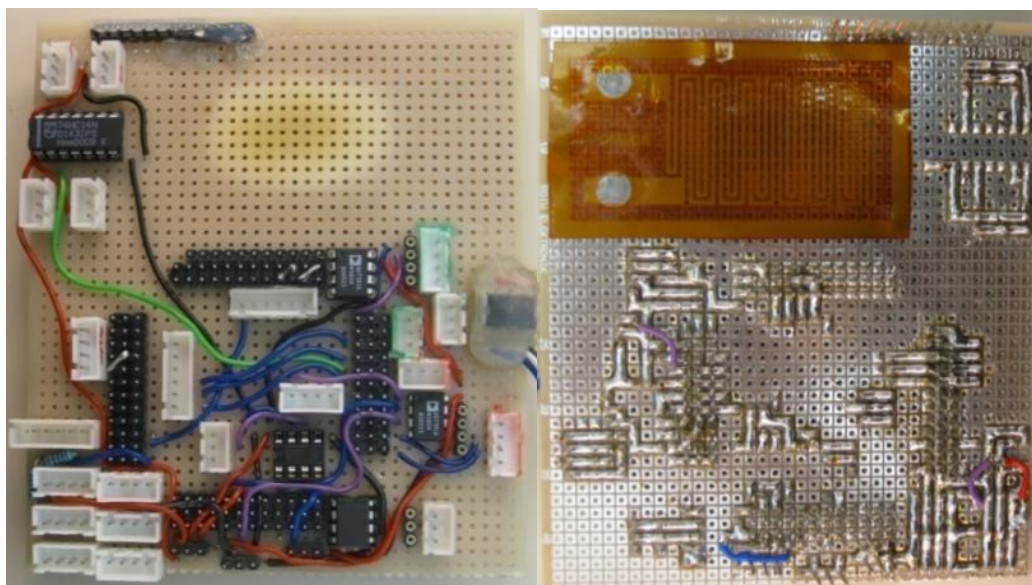


Figure 3.47 On top prototyping board built for the experiment

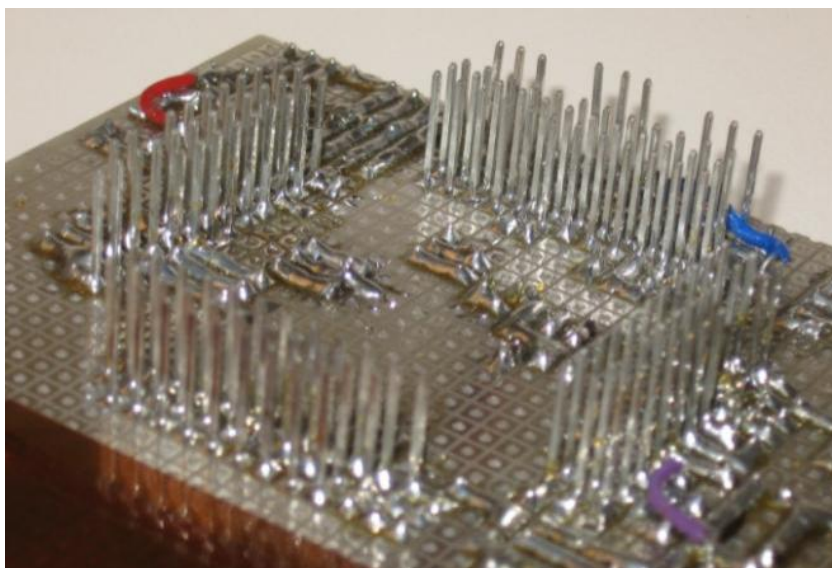


Figure 3.48 Connection pin to the evaluation board

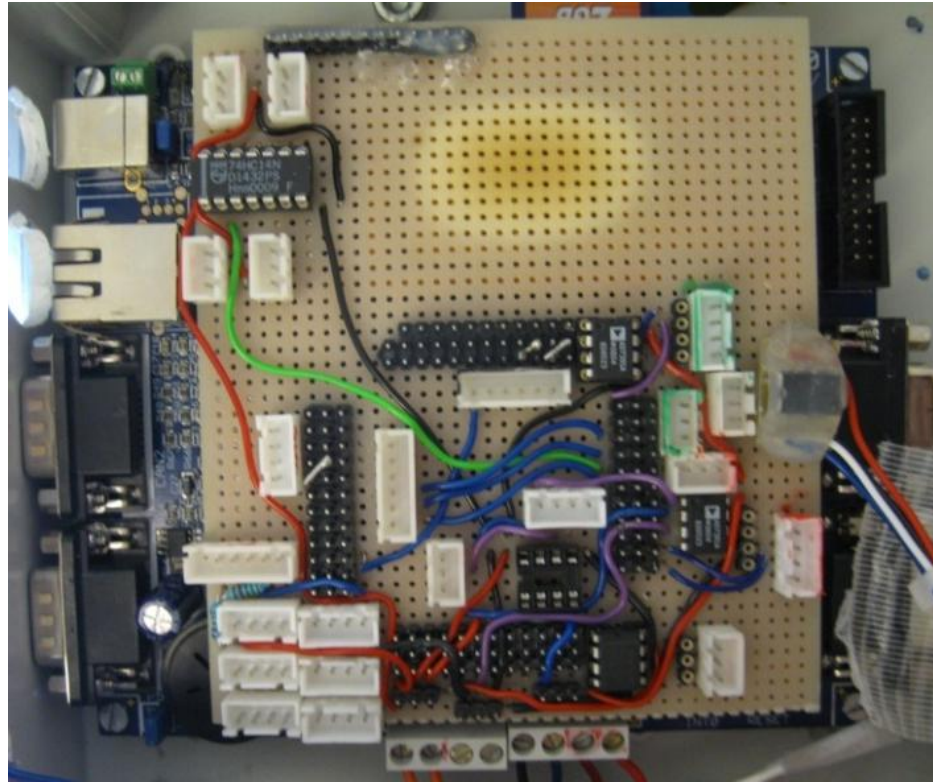


Figure 3.49 Evaluation board with prototyping board on top

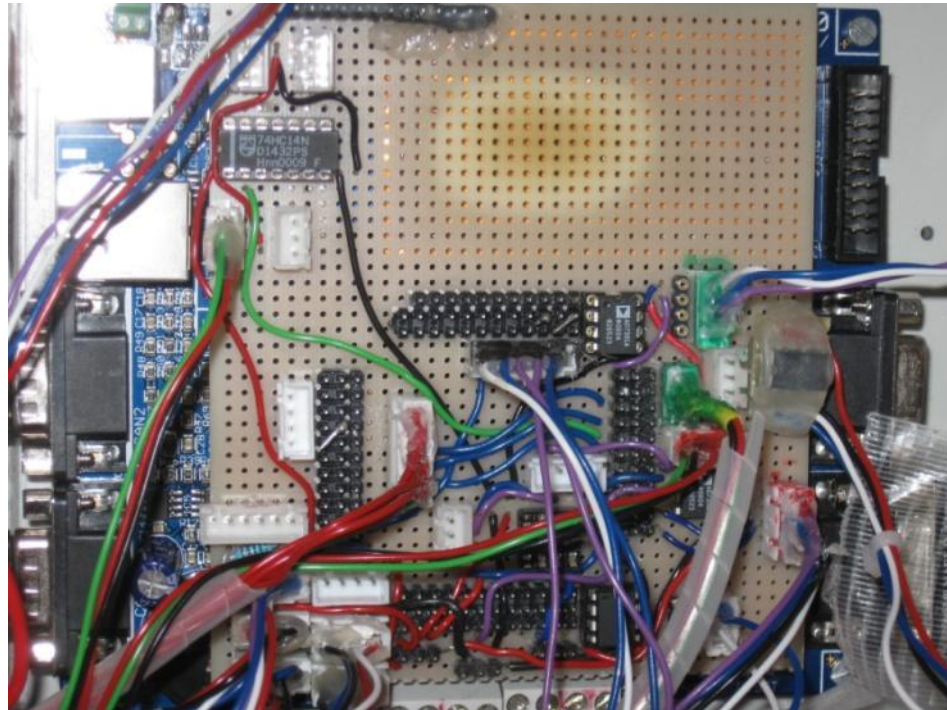


Figure 3.50 Evaluation board and on top prototyping board with complete connections to other modules.



The electrical interface between the MAIN Payload and the E-Link was the Ethernet, physically connected via MIL-C-26482-MS3116F-12-10P connector.

3.8.3.11 Single Point Failures Prevention

The whole power subsystem is designed in such a way that it tries to reduce the single point failures as much as possible:



- a) Multiple battery distribution protected by fuse against excessive current and isolated by diodes
- b) Multiple battery sets feeding main power system (Supply1, Supply2,), protected by fuse.
- c) All regulators doubled and isolated by diodes.

ii. *Interface between boxes*

The possibility of single point failure was reduced by implementation of the following:

- a) Main power supply connectors rated IP65
- b) All pins in the power connectors and PCB doubled
- c) Multiple wires used for connecting power supply box with the rest of the system

iii. *Microcontroller box, sensors*

- a) All critical sensors doubled
- b) Microcontroller and sensors isolated from the motors and the main power supply

List of Single Point Failures:

i. Power Subsystem

Name	Description	Prevention	Note
P1-Excessive heating	Thermal runaway of diodes-domino effect (higher temperature, lower Vf, the diode will conduct more than the others).	Diodes equipped by heat sink or silicon pasta used to connect diode with the cover, temperature monitoring of the cover diodes with low Vf.	-
P2-Failure monitoring circuit	Isolation amplifier, optocoupler or multiplexer fail.	High quality components.	This may not be consider 100% single point failure but since the status of the power across the emergency motor is unknown, experiment may not continue.
P3-Contamination	Water getting inside	Connector and the box	-

	the box or batteries.	must be rated at least IP65, so low pressure jets of water do not penetrate, battery equipped with protection cover.	
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Figure 3.52 Single Point Failures of the Power Subsystem

ii. Interface between Electrical Subsystems

Name	Description	Prevention
I1-Connector	Connector gets loose	All connectors properly screwed, cables mounted to the structure to reduce stress on connectors.
I2-Pin in connector	Pin in the connector get disconnected	All power and critical signal pins doubled
I3-Wire	Wire gets disconnected	For power distribution, using multiple wires between the sub systems

Figure 3.53 Single Point Failures at the Interfaces of the Electrical Systems

iii. Microcontroller box, sensors

Name	Description	Prevention
M1-Microcontroller	Microcontroller or crystal fails	Isolation between main system, motors and the microcontroller
M2-ZigBee	ZigBee fails	Thorough testing of the Zigbee Modules

Figure 3.54 Single Point Failures at the Microcontroller BoxSensors



The FISH shall employ two SAFT batteries (SAFTLSH 14 "Light") rated at 3.6 V. The maximal current is up to 1.3 A and the capacity is 3600 mAh. Figure 3.27 shows the power budget for the components that shall be implemented.

Unit	Current Consumption (mA)	At voltage (V)	Power (mW)	Power dissipation (mW)	Units	sum (mW)
Microprocessor	125	3.3	412.5	1500	1	412.5
Colibri M8002.D	0.4	5	2	0	3	6
ADS1274	50	5	250	285	1	250
ADS1274	18	3.3	59.4	0	1	59.4
ADS1274	0.15	1.8	0.27	0	1	0.27
HMC6352	1	3.3	3.3	0	1	3.3
LIS3L02AQ3	0.85	3.3	2.805	0	1	2.805
Xbee	45	3.3	148.5	0	1	148.5
					Total	882.775
Batteries	Voltage(V)	Current (Ah)	Number of units		Total Power (Wh)	
SAFTLSH 14 "Light"	3.67	3.6	2		26.424	
Total amount of current			250 mA			
The power supplied by the batteries			3600 mAh			
So the system could be running for about			14.4 hours			

ASC 5421 Capacitive Accelerometer is an Accelerometer set based on Colibrys 8000 Family that integrates three single axis accelerometers, along with



manufacturer recommended electronics to create a Ultra Low Noise Triaxial accelerometer system with amplified output. This unit is repacked in a High shock resistant, gas damped, and aluminium package. Having a good bias, zero g Output of typically ± 50 mV and noise as low as $7 \mu\text{V}/\text{RootHz}$ along with a maximum current consumption of 2 mA, make it a perfect choice for our project. Usually these accelerometers are used for Vibration monitoring, high speed trains, seismic measurements and military applications.

Colibry 8002.D Accelerometer is a MEMS capacitive accelerometer sensor that has an excellent bias stability that will enable the system to accurately measure the acceleration, especially when approaching the state of microgravity. This sensor is a one-axis accelerometer, so three units have been included in the design to be able to sense X, Y, and Z.

ADS1728 Analogue to Digital Converter is a quad, simultaneous sampling, 24-bit Analogue-to-Digital Converter. This particular converter was chosen because it can measure eight channels simultaneously, allowing us to be able to get the data from all the high precision accelerometers, the gyros and the temperature sensor embedded to one of the accelerometers with a 24 bit resolution and at very high sampling speed (up to 128 kSPS). It also can communicate with our microprocessor via SPI and Frame-Sync.

Xbee Pro 868 Module is an RF module that transmits in the 868 MHz ISM frequency band. This frequency range is not used by any system components on board the balloon. There is therefore no risk of interference. These radio modules have very low power consumption and have a good range that will hopefully be able to communicate both payloads for the whole mission.

In addition to these very important components, other components were added to add redundancy to the system in case of failure as well as to have more data available to be able to know with more detail, what happened during the whole mission. These components are a set of three ADXR150 Gyros, a HMC6352 Compass, and a LIS3L02AQ3 three axis accelerometer.

3.8.4.3 Features of the FISH

- Redundancy of data acquisition: there are two sets of three axis accelerometers that measure the acceleration of the FISH at all times, so in case the high precision main accelerometer pack was to fail, the backup, that although not as accurate, would still be able to still acquire some good data, not as accurate but enough to get some useful data.
- Redundancy of data storage: The FISH was be saving all the information on the internal micro SD card and was also designed to transmitt it to the MAIN Payload, which was to store it and retransmit to the ground station. In this way, the data was to be stored in 3 different places, to avoid losing it all if one of the storage systems failed, and even in the case that the internal FISH micro SD card failed, at the same time that the wireless link failed, the



microprocessor itself had 512 kbytes of memory available to enter an emergency mode that would be saving all the recorded data, while the wireless link or the internal memory could be recovered.

3.8.4.4 Interface with Accelerometers

The most important part of the FISH subsystem is the acceleration data acquisition, for this endeavour the ASC 5421 unit will be held next the PCB board as it is already encased and calibrated, and will have from 9 output wires that will do straight into the FISH electronics Board. Inside the board the signals from each of the axes will be taken into the ADS1724 high resolution Analogue to Digital Converter. This converter is capable of sampling up to 52,734 samples per second in high resolution mode, but as the accelerometer's data will only change at a rate of 200Hz or 200 times per second, so we will be over sampling the acquired data in order to be able to average the incoming data and with this filter it for noise ensuring that the incoming data is valid.

In Figure 3.55 the connection from the three high resolution accelerometers and temperature sensor P10 to the ADS1728 is depicted, in it, it can also be seen that P3 includes test point for every incoming line and 100 ohm resistors to protect the lines from excessive voltage during the test phase or even in flight. In this screenshot the voltage regulators can be seen in the upper right, these were changed from the previous design for two reasons. First because the components came in a very small package the problem is the thin air in high altitudes doesn't transfer heat away as effectively as cold air on sea level. So a small case might not be able to dissipate 0.5 W. Usually the regulators have a temperature protection so heating the small package with 0.5 W will turn it off and the experiment will shut down. Only way to dissipate heat is with low heat resistance and big area. Normally small components have neither of those properties. And second because this ones can all take the voltage straight from the VIN Battery supply input, and there's no need to cascade regulators or need to put extra electronics to split the voltage to make it low enough for the voltage regulator to use. For more detailed schematic drawing please refer to Appendix 3.

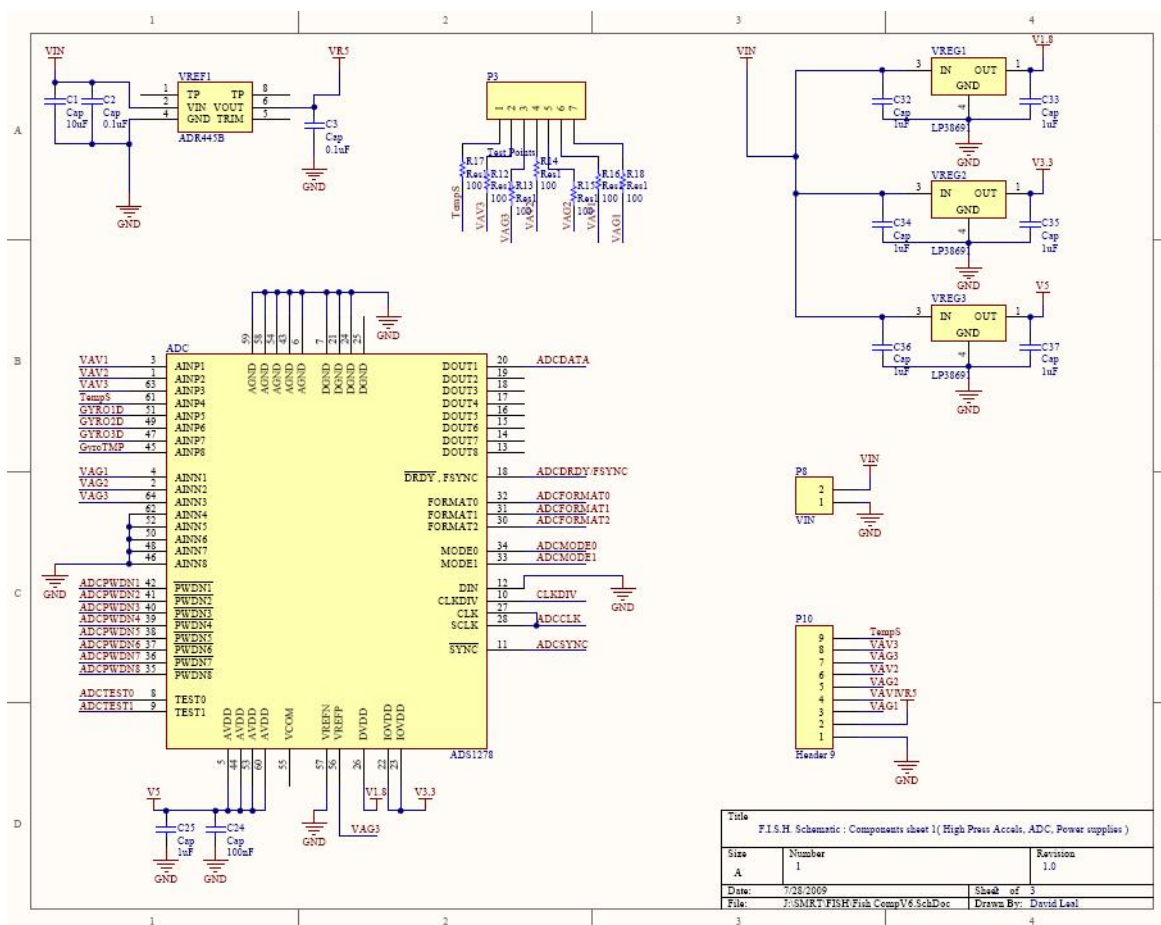


Figure 3.56 FISH ADC to Accelerometer Connections.

3.8.4.5 Microcontroller and Memory

The LPC2364 ARM7 microcontroller is a complex microcontroller that has many peripheral and need a moderate amount of electronics in order to run it. In order to assure that the micro controller would properly run, the KEIL SOFTWARE MCB2300 v3.0 evaluation board for this micro controller was used as a reference, along with the datasheet of the manufacturer to design a system that would have the appropriate electronics to have the micro controller running without adding to much electronics, as this particular board is very limited in size.

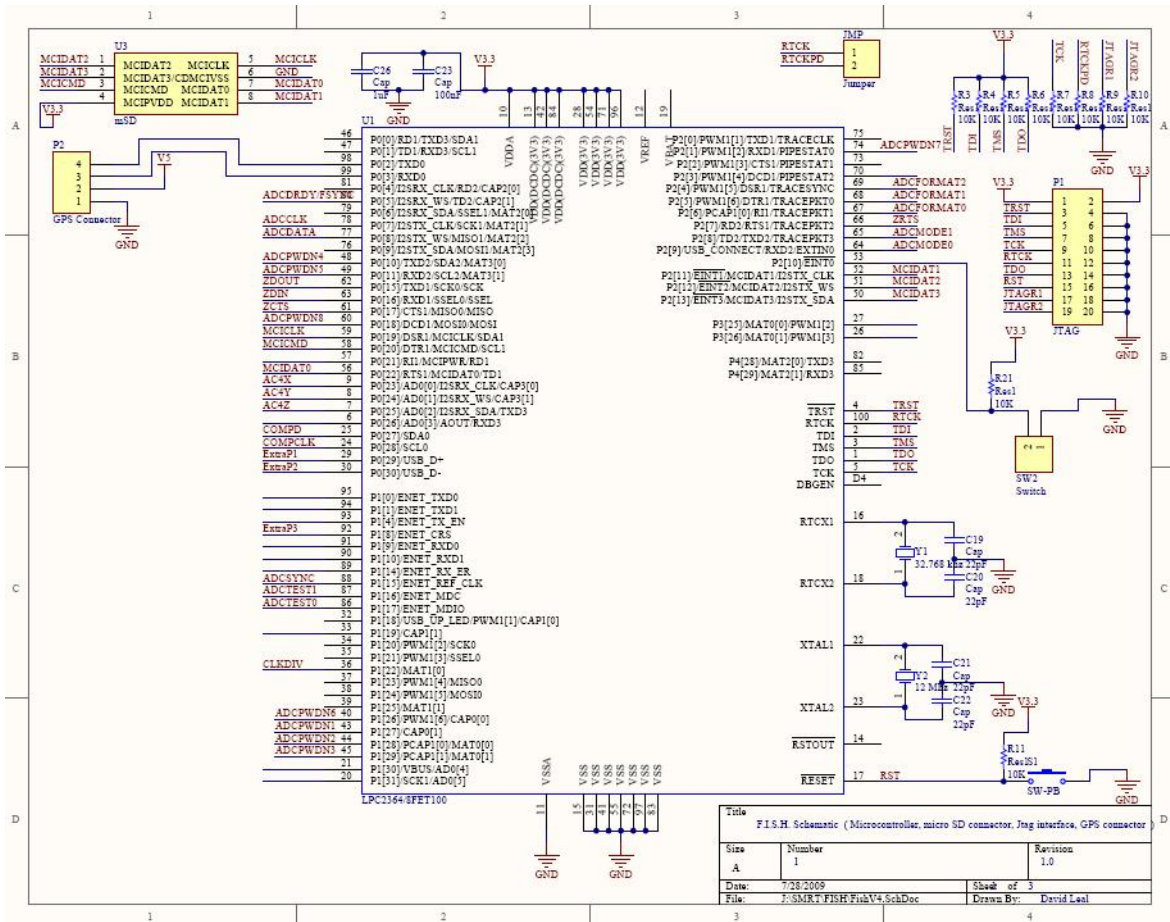
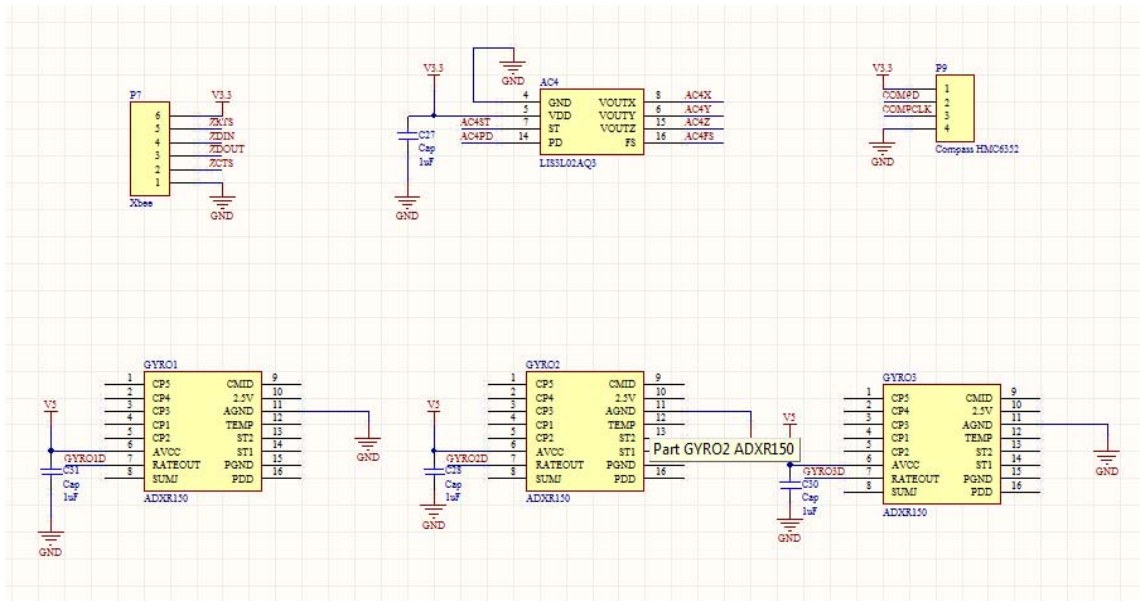


Figure 3.57 Microcontroller and Memory Schematics.

In Figure 3.57 the connections from the micro controller to its basic operating circuitry are shown, as well as the interfacing peripherals added for programming and debugging it (JTAG) and the micro SD memory card mount that will provide the system with enough memory to store data from the whole mission.



An additional three axes linear accelerometer was added, this for redundancy of data and also in case the main high precision accelerometers would fail then the data received from this one will still give us a fair idea of what happened during the flight., Three Gyros and Wireless communication radios were also added to the design and their schematics can be seen in Figure 3.58



3.8.4.7 Special Considerations

3.8.4.8 FISH PCB Layout Design

The PCB layout for this system was a big challenge, as there's many sensitive components and the space was very limited in order to comply with the requirements of the mechanical subsystem, so priority was given to the most critical component, the High accuracy accelerometers to have the shortest path to the ADC.

One important thing to consider, is that the ASC 5421 has different available outputs, and the FISH will be using differential signals, which means that for each axis, two wires will go from ASC 5421 to the PCB board, one being signal and the other one reference voltage, this way totalling 9 lines including power, ground, acceleration signals and the temperature analogue signal provided by the accelerometer..

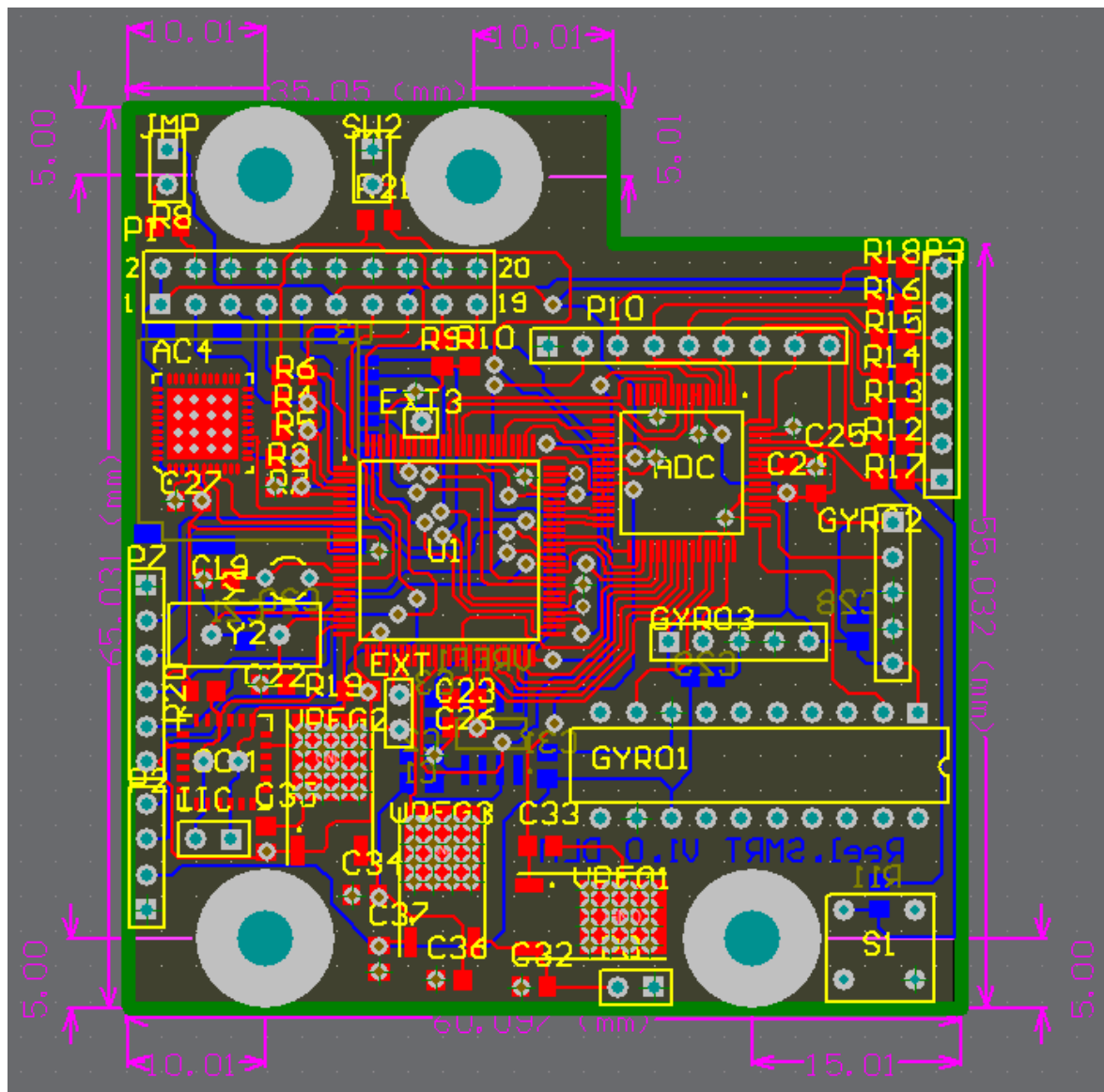


Figure 3.59 Top View of the FISH PCB Board v0.9

The Fish PCB is a four-layered PCB board that has two layers for signals and two ground planes that help reduce noise and helps ensure that all integrated circuits

within a system compare different signals' voltages to the same potential. The two signal layers and the ground planes are pictured in Figure 3.60, both ground planes have the same layout as first they were designed to be separate grounds for analogue and digital signals but according to some recommendations of experts, it was better opted to just have two ground planes for all, for further details please see the Appendix 3.

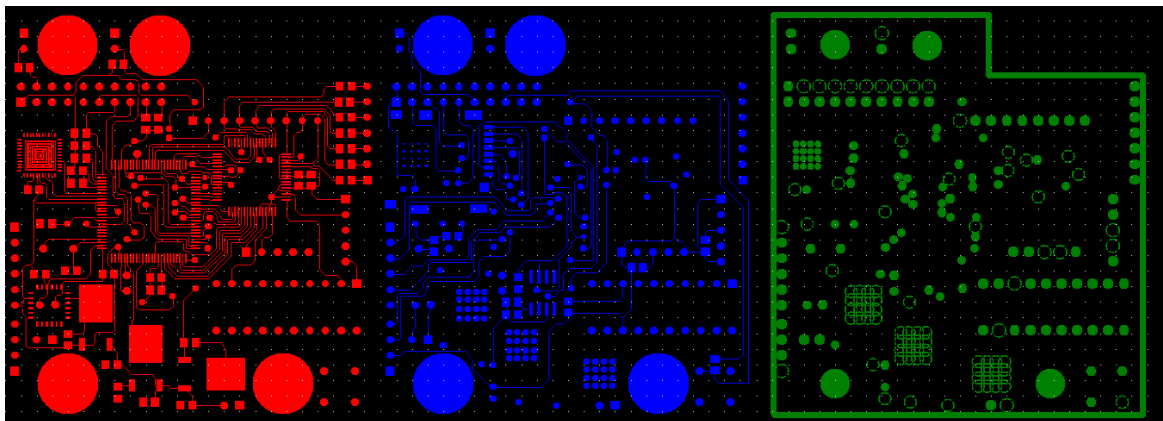


Figure 3.61 Top, Bottom and Power Layer

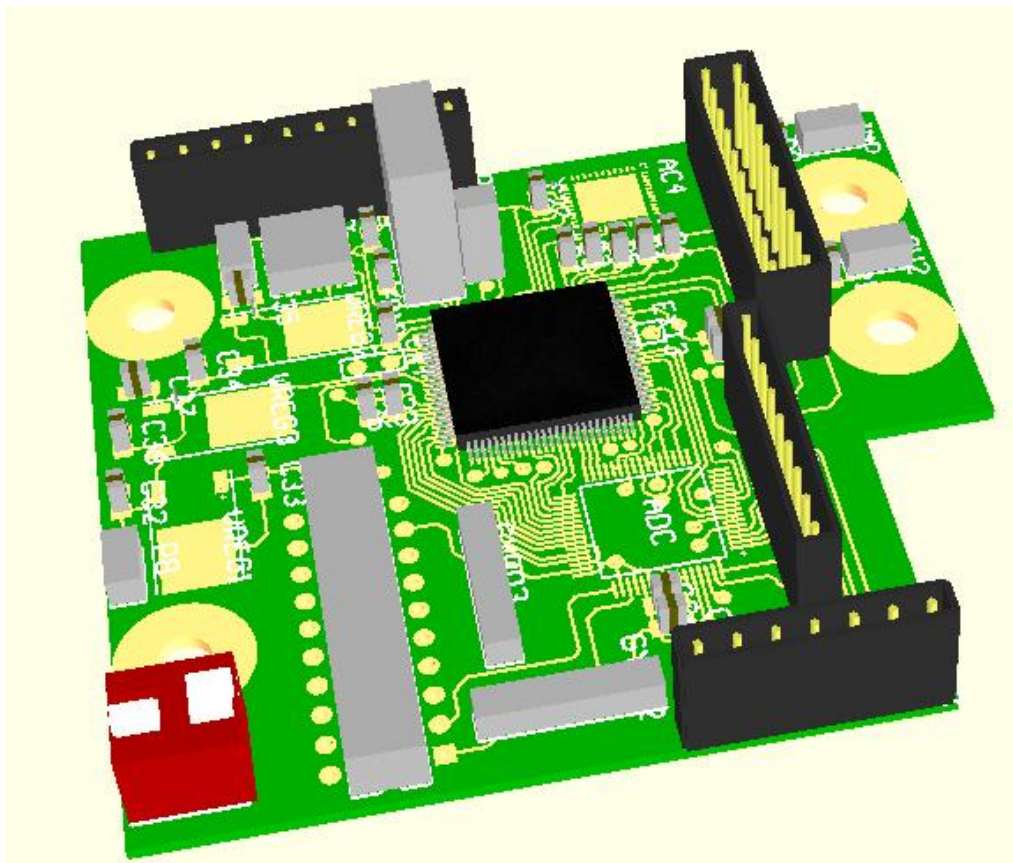


Figure 3.62 Simulated 3D View of the Actual FISH PCB Board

3.8.4.9 Calibration

The Sensor pack ASC 5421 came with a factory calibration provided by Advanced Sensor Calibration Company (ASC). ASC has its own ultra-modern Spektra calibration facilities on the premises, which have been recently calibrated by Spektra. They pointed out the calibration they provide is well respected in all of Europe and is usually enough for any German company at least. They calibrate by pendulum and standard sinusoidal calibration methods, as well as with shake test.

The sample calibration provided by ASC was satisfactory for vibration testing and will try to provide static calibration as well, in case they are not able to provide it we will go with another 3rd party calibration. One such calibration has already been quoted by Spektra including :

- Static Calibration uni-axial
- Static calibration of an accelerometer in the gravity field at $\pm 1g$ and check of cross sensitivity (sensitive axis in 90° direction to gravity field)
- positioning uncertainty 0.1°





Figure 3.63 Picture of Calibration Equipment Provided by Spektra



3.8.4.10 FISH Summary

The FISH is the dropped payload system that shall acquire the acceleration data with the ASC 5421 accelerometer in all three axes via a ADS1728 Analogue to digital converter, which will send the data acquired to the LPC2368 microprocessor. The microprocessor will also be receiving analogue data into its internal ADC from three Gyros, and one extra three-axis LIS3L02AQ3 accelerometer that will be used as a backup in case the other accelerometer fails. The microprocessor will be storing all this data into its on-board micro SD memory card, along with a timestamp. At the same time, it will be communicating with the MAIN Payload and sending as much data as possible to be backed up, and also to be retransmitted to the ground station for immediate analysis and system status updates.

3.8.5 Data Management

3.8.5.1 Communication FISH- MAIN Payload

In the FISH, two categories of sensors can be found:

- Scientific sensors
- Control sensors

The purpose of the scientific sensors is mainly to measure values needed for post-processing. Those sensors on the FISH are:

- Accelerometers (two in each of the three body axes)
- Gyroscopes (about all three body axes)

All sensor data is stored on a memory card (SD-card) continuously during the experiment. In addition, all data is transmitted to the payload using a RF serial communication link. However, the transmission of all data cannot be performed in real-time, since the data rate of those modules (24 kBit/s maximum) is too low for the large amount of data generated by the sensors (~174 kBit/s) (see Appendix S.1 "Calculation of Net data rate of FISH sensors").

Therefore, during execution of an experiment (in either the slow reel or free-fall mode) the amount of transmitted sensor data is reduced. As soon as the FISH is back in the FISH Bay the remaining data is transferred to the payload's storage.

In general the communication between the FISH and the MAIN Payload is bidirectional: sensor data is sent from the FISH to the MAIN Payload and experiment status data messages (like "slow reel in progress" or "emergency recovery mode activated") is transmitted from the MAIN Payload to the FISH. However, if one direction fails to function correctly, the experiment can continue in



unidirectional mode. All status data messages are acknowledged by sending the data message back to the MAIN Payload.

3.8.5.2 Error Detection

The RF radio modules (xBee Pro 868) do not provide any error detection or error correction algorithms. Therefore the quality of the data transmission is vastly improved by adding a checksum error detection part to each transmitted block of data. If an erroneous sensor data block is detected on the MAIN Payload side, a status data message is sent to the FISH including the time stamp of the sensor data block that needs to be retransmitted. Status data messages received from the MAIN Payload are protected by a checksum part as well, although they are not requested again. Instead, if no 'acknowledge data' message is received within a certain time at the MAIN Payload, the sensor data message is retransmitted. The protocol specification that maintains the connection and error correction is in Appendix 4.

3.8.5.3 Communication MAIN Payload – Ground Station

Similarly to the FISH, the scientific sensors located within the MAIN Payload are accelerometers and gyroscopes. The values measured by these sensors are stored on a local flash memory (SD-Card). In addition, all sensor data received from the FISH is stored on that SD-Card as well.

Since the MAIN Payload sensors generate almost the same amount of data as the FISH, the total data rate to the SD-Card nearly doubles ($2 \times \sim 174 \text{ kBit/s} = \sim 288 \text{ kBit/s}$). But still this data rate is well below the maximum data rate a SD-Card can handle ($\sim 8 \text{ MByte/s}$, see appendix 3).

The MAIN Payload also houses the main microcontroller, which controls the entire experiment. In addition to that it also controls the communication between the reel.SMRT experiment and the ground station.

For that purpose, the balloon's E-Link telemetry system is utilised. It supports data exchange with the ground via an Ethernet connection.

This connection is used to download status information to the ground station to supervise the experiment from the ground. If necessary, the uplink capability of the E-Link connection is used to send telecommands up to the experiment.

Depending on the bandwidth available on the Ethernet link, it is planned to send down at least parts of the acquired sensor data during the flight. This is not mission critical, however, but it helps to bring the valuable data into a safe place so that a satisfying data analysis can be done even if the whole experiment gets damaged.

Without the downlink of sensor data, the data rate for the downlink is very low. During the reeling process, the number of status messages can go up to 15 in



about 5 seconds. With a status message length of 20 Bytes, this sums up to about 60 Bytes/s.

The uplink telecommands are executed manually reducing the number of messages to approximately one per second or 20 Bytes/s.

If the downlink bandwidth is available, all sensor data could be downloaded with a data rate of ~300 kBit/s. When missing parts have to be retransmitted, this value could reach approximately 600kBits/s.

All status information is transmitted using TCP/IP packets. This allows the use of the error detection/correction/ functionality of TCP/IP. If the delay time of the telemetry link is very high (> 1 second) the sensor data can also be down-streamed using the UDP connectionless packet type. Then, however, no error correction functionality is available. The protocol specification can be found in Appendix 4.

3.8.5.4 IP Camera Communication

The IP camera is directly connected to one of the E-Link Ethernet ports and powered by an independent set of batteries. The images and audio captured by the camera are sent down to the Ground Station computer. There a webserver-based application displays the images to the operator. In addition, all downloaded images and movies are stored on the hard disk.

3.8.6 Radio Frequencies

For data transmission between the FISH and the MAIN Payload a radio link is used. It is based on the xBee Pro 868 radio modules. They transmit in the 868 MHz ISM band.

3.9 System Simulation

The system simulation may be found in Appendix 5.

3.10 Data Processing and Analysis

The post-processing was to be set up and tested using data from system tests before the flight. It was arranged in MATLAB so that it could be done with minimal effort from the team during the flight. However, a software error from an incorrect version being loaded into the system prior to flight meant that the system could not transfer high data rate mode FISH data to the ground station. Consequently, the acceleration data from the drop was recorded on the SD card of the FISH (as demonstrated during testing). Thus, the data received at the ground station was only the FISH acceleration data prior to the drop as well as the temperature data and IP camera data.



As some aspects of the post-processing were expected to be relatively simple, partial processing was intended to be done during the flight itself to quickly analyse data and to look at maximum accelerations so that operations can be modified if the need is identified. This was to be done by transferring the data being sent to the ground station onto a separate computer to handle the processing there.

Individual drops were to be identified by timestamps and plotted in this phase. With this, it would have been possible to identify the times in which the FISH drops are occurring. This worked successfully for the single drop made.

The data from the accelerometers that was to be transmitted needed to be adjusted for position and drift (drift was to be examined before and after the flight). This was to be done by designating a pre-drop time so that the position of the FISH within the payload could be determined. The data from the gyros was to be used to determine the drop paths relative to the balloon for possible troubleshooting. Using the adjusted position (including errors from the adjustment), the position of the FISH (in three dimensions x, y, and z as well as x vs. y, x vs. z, and y vs. z) during drop could have been plotted during its fall. This was to be used for problem analysis during the flight itself.

The acceleration data for all six accelerometers was also to be plotted (acceleration vs. time) after adjustment for the acceleration due to gravity (having been calibrated on Earth to treat conditions under gravity as the zero level). This is the most important data for the scientific evaluation of the experiment. From these plots, maximum accelerations during freefall could have been identified as well as evaluation of the quality of the reduced gravity environment. These are also important for the in-flight troubleshooting, if acceleration spikes are seen during braking, this could have been adjusted for.

After the flight, data from the accelerometer on ground was to be analysed to determine if a drift had occurred, with this it would have been possible to calculate the drift over time and increase the reliability of the results.

Post-flight analysis of the sensors for drift during flight could then be used to update the data to be more accurate. The plots could then have been examined to determine where the greatest accelerations occurred during the drops. In each drop, the different accelerometers would have been compared to see in which axis the acceleration was greatest. Different drops would have also been compared by total acceleration; this would have been compared to other data taken to see if temperature or gondola speed has an effect on the acceleration. This data was to be compared to full system tests conducted before and after the flight. In this way, the relative quality compared to drops on ground could be examined.

However, until the FISH has been located on the ground, the acceleration data from the drop cannot be processed in the manner discussed here.



4 REVIEWS AND TESTS

In this chapter the dates, locations, participants and the main recommendations of the review boards following each review are summarised. To date, the ESW, PDR and CDR are the only reviews to have been completed.

4.1 Experiment Selection Workshop (ESW)

Date: 3-5 February 2009

Location: ESTEC, Noordwijk, The Netherlands

Participants:

a) Experimenters

Katherine BENNELL

Mark FITTOCK

Mikulas JANDAK

David LEAL MARTINEZ

Campbell PEGG

b) Review Board

Representatives of ESA, DLR, SSC

During the ESW, the experiment proposal was presented along with preliminary high level system designs. This included the objectives of the experiment, background information, team structure, technical concepts, interfaces, data collection, safety issues, financial and scientific supports as well as the outreach plan.

4.1.1 Recommendations of the Review-Board:

That the reel.SMRT team must:

1. Provide a detailed risk analysis and design of a safety system
2. Be very careful with planning and ensure sufficient time to implement the safety system
3. Provide more details on your braking system and the related frictions
4. Give more details on how the system will be tested
5. Assess the drift of the FISH during a drop and its consequences on the whole system and the measurement accuracy.



4.1.2 Response to the Recommendations of the Review-Board:

1. Refer to Section 0 and individual subsystem designs. Particularly, mechanical risks are addressed in Section 3.5.3.
2. Refer to Section 5.1.
3. Refer to Section 3.5.2
4. Refer to Section 4.5
5. Refer to Section 3.9.

4.2 Preliminary Design Review - PDR

Date: 22- 27 March 2009

Location: Oberfaffenhoffen, Germany

Participants:

a) Experimenters

Katherine BENNELL

Mikulas JANDAK

Mikael PERSSON

Jan SPEIDEL

b) Review Board

Olle PERSSON (Chair)

Mikael INGA

Andreas STAMMINGER

Harald HELLMANN

Josef ETTI

Helen PAGE

Cyril ARNADO (Secretary)

Jutta STEGMATER

During the PDR, the experiment preliminary designs were presented along with risk analysis, test plans and a justification of the system. This included the delivery of the first SED including detailed objectives and requirements of the experiment, designs of each subsystem, data collection, safety issues, financial and scientific supports as well as the outreach plan and flight requirements plan.

4.2.1 Summary of Panel Comments and Recommendations of the PDR-Board

(full report in Appendix 1.4):

1. Possible collaboration with Delta Utec for testing to be discussed with SSC and ESA.



2. Should assess the impact of low pressure, temperature and humidity (ice) on gear, motors and lubrication.
3. Parachute system needs to be elaborated by CDR.
4. Wireless should be better assessed.
5. Ultrasound sensors to be done if time allows it.
6. Accelerometers are being chosen. Should be done by CDR.
7. No autonomous mode. Needs to be turned on/off remotely.
8. The parachute system needs to be looked into very carefully.
9. Need to assess the behaviour of the system if the gondola oscillates along the X-axis.
10. Fins. Need more work on the FISH flight dynamics.
11. If the MAIN Payload fails to operate, there are no emergency brakes. The FISH will separate and the parachute will be triggered.
12. Detection of failure fall and experimental free-fall is made by pressure sensor + timer. Need more details in the SED, Need to take into account the quick variations of pressure if the gondola is tumbling.
13. EMC needs to be assessed as soon as possible.
14. Website could be more user friendly.
15. Good outreach plan – capitalise on the fact that team members come from many different countries - try to target journalists from their home towns.
16. Elaborate plan for outreach payload.
17. Safety aspects and frequency issues will be a go/no-go issue at CDR
18. Electronic design to be detailed.
19. Thermal/mechanical analysis to be performed.

RESULT: PDR PASSED

4.2.2 Response to the Recommendations of the Review-Board:

1. Testing for Delta Utec is not currently planned due to time-limitations and high cost. It is a possibility for future work on this system.
2. The impact of low pressure and temperature will be tested at IRF facilities. The impact of humidity and lubrication of gears and motors will be assessed through industrial standards which guarantee operations under such environments and without leakage of the seals (standard IP 60 for seals).
3. The parachute system has been developed significantly since the PDR. A spring-loaded pilot chute and CYPRES Unit as provided by Olle Persson from



ESRANGE, now comprises the parachute deployment system. For more information refer to Section 3.5.5.1

4. ESRANGE has approved an interference test to be conducted during late May/ early June. See 17 for more details of the wireless system.

5. Ultrasonic sensors shall not be implemented, as the difficulty with positioning the sensor on the FISH makes the use of the ultrasonic sensor quite impractical. The response of the motors (39 ms with a speed of 70 m/ 60 s would also be inadequate for such a system. Instead, the position will be sensed after 4. cm when the FISH enters the FISH Bay.

6. The accelerometers have been chosen as the ASC 5421 model, which come pre-calibrated. See Section 3.8.4.4

7. The reel.SMRT system no longer involves any autonomous mode, with all modes of the system occurring from command from the ground station through the E-Link system.

8. See 3.

9. The enclosure of the FISH within its Bay in the MAIN Payload is secured via low-density expanded polystyrene (EPS) filling which will comply to the geometry of the FISH without impeding operations, refer to Section 3.5.1. The final design is to be constructed as the assembly of the FISH structure within the MAIN Payload occurs. However, there is great confidence in the structure and damping characteristics of the EPS material.

10. There are no longer any fins on the FISH, due the difficulty in their alignment. The FISH has undergone a complete redesign to increase the static margin, with the value optimised to 0.65 with respect to diameter over a series of design iterations. Despite that it is less than 1, it could not be increased any further without major increases in weight to the system or alternate internal components. This system remains sufficiently stable as due to the low atmospheric density, there is little force on the centre of pressure to stabilise the system, despite its value of static margin.

11. In the rare event the MAIN Payload power fails with the bail open, the FISH will be braked. This is because the reel will be equipped with a power-off brake, either from the internal brake of the reel or via a brake on the motor. Additionally, the line guide mechanisms will also be self-locking via a power-off brake on its shaft.

12. A pressure sensor and timer are no longer used for the parachute deployment mechanism. A COTS CYPRES Unit is now employed. For more information see Section 3.5.5.1.

13. The EMC shall be assessed by a test at ESRANGE as soon as the electronics has been constructed and ready for testing.



14. The website has been updated since the PDR to be more user friendly with additional updates, including the press releases. For more information refer to Section 6.5.

15. The outreach plan has undertaken development, with press releases for each team member for their local publications issued. These press releases may be found in Appendix 6.

16. The plan for the outreach payload has been finalised. For details of the competition refer to Section 6.3.

17. An investigation into the frequency performance of the FISH- MAIN Payload communication system has been conducted. It was determined that the frequencies of the system presented at PDR would most likely interfere with the BEXUS E-Link system. As such, the components are no longer xbee, but xbee pro 868, which transfer at 868 MHz, outside that of the E-Link system.

18. The electronics design has been detailed, with all components finalised and PCB design completed. For more information refer to Section 3.8 and Appendix 3.

19. Thermal and Stress analyses have been performed for both the MAIN Payload and the FISH. For summarised results refer to Section 3.5. For detailed results refer to Appendix 5.

4.3 Critical Design Review - CDR

Date: 4 June 2009

Location: ESTEC, Noordwijk, The Netherlands

Participants:

a) Experimenters

Katherine BENNELL

Mikulas JANDAK

Mikael PERSSON

Jan SPEIDEL

b) Review Board

Olle Persson

Harald Hellmann

Bruno Sarti

Koen de Beule

Roger Walker

Helen Page (Secretary)

Martin Siegl

4.3.1 Recommendations of the CDR-Board:



1. Look at the stress due to the flight environment. Consider the size and weight of the experiment, consider straps and mounts to mitigate the bending moment on the MAIN Payload structure.
2. Need to know that the construction is solid enough to stay on the gondola- hole would allow things to fall out.
3. Cables for FISH – inside or outside?
4. Try to reduce mass of FISH – consider having radio on the side of the gondola
5. Friction during braking will degenerate the line over time. Swivel might also weaken the structure. Recommend to analyse/test how this will affect performance and whether there is a risk of cable break.
6. Redundancy on servos in one system doesn't always work – consider connecting them in parallel if redundancy is really needed or using one that can be disabled.
7. Are cameras feasible and compatible?
8. Estimation on cold battery in FISH – active thermal control would improve efficiency.
9. IP cameras should always be on but they are not currently included in mass or power budgets.
10. Regulators in FISH have no cooling fins – calculate to check that this will be ok.
11. Consider using smaller connectors.
12. Fuses can be a risk – calculate reserve and pay attention to mounting. Only use if really necessary – choose high reliability fuses.
13. Consider including GPS in FISH to locate it if the line breaks.
14. Should perform link budgets and bandwidth assessment.
15. Interference tests need to be thorough
16. Clarify what will be measured during system tests, in particular EMC test is important and needs to be well-defined – relate tests to requirements.
17. Consider measuring friction on the line during reel test. Allow time for making adjustments/improvements based on test results.
18. Frequency risk are not mentioned and some risk probability numbers are not realistic.
19. ICD to launcher should be better worked out
20. Frequency assessment is still a concern – pay attention to harmonics and test very thoroughly.



21. Request has to be submitted to Swedish authorities for transmission – make sure it is done well ahead of time.
22. Plan a 1m drop test during pre-flight interference test on Hercules.
23. Countdown list – add setting of CYPRES.
24. Website picture gallery and blog to be added
25. Take care to define definite selection criteria for the outreach competition.

RESULT: CDR PASSED

4.3.2 Response to the Recommendations of the Review Board

1. Further mechanical analysis was performed and it was determined that for the case of a high load and vertical bending moment that the MAIN Payload structure endures high stress levels. To mitigate this, cables and straps have been designated for use. The details of this design may be found in Section 3.5.1.
2. This has been addressed. Please refer to Section 3.5.1. and the Mechanical Appendix.
3. Cables for the FISH shall be on the inside of the FISH, so as not to risk trapping or pulling the wire on the compliant geometry of the MAIN Payload.
4. As in 3.
5. Friction during braking will degenerating the line over time is not a problem because of the short time span of the experiment and the low number of drops. Any minor wear does not prevent the system from reaching the objectives as at this stage the experiment is a prototype to prove a concept, not a concept for a sustained-operation apparatus. The line is sufficiently durable to last the reel.SMRT experiment.
6. The design of the bail opening mechanism has been redesigned in response to this issue. Please refer to Section 3.5.1 for the details of this new mechanism.
7. A single IP camera has been deemed feasible and compatible. The camera will operate on a separate power supply to the rest of the system. For further details of the implementation of the IP Camera, please refer to Section 3.7 .
8. It is currently estimated that the batteries used on the FISH do not required additional heating. Those selected have a low temperature limit beyond standard flight conditions. However, if integration testing demonstrates that heaters should be implemented, additional GPIOs are ready to be added as required.
9. The IP camera is to be powered up from a separate battery pack consisting of three Li-Ion pieces each rated at 3.7 V with the nominal capacity of 2300 mAh. This has been considered in both the electrical and mass budgets for the system.



10. The regulators have changed since the CDR designs. The new regulators connect their heat sink directly to the ground layer of the board. In this way, the heat is both dissipated and used to heat the board.

11. This was considered, however the components chosen were those readily available in the laboratory used for construction and the designer is experienced with the current connectors.

12. After careful consideration of the advantages and disadvantages of fuse implementation, fuses are no longer part of the MAIN Payload electrical design. This is primarily because the controllers for the motors have a current limit as do all the dc/dc converters. These features effectively minimise the potential risk of high current flow and hence overheating and explosion risks.

13. Since the FISH's limit of the mass budget has been already reached, it was decided not to use a GPS sensor on board the FISH. Also, it cannot be guaranteed that the FISH would land in a position that the GPS antenna can receive valid data. Therefore another approach was found: The GPS position of the gondola is sent to the FISH every second. In case the tether breaks, the FISH switches to recovery mode and starts transmitting its last known GPS position. The position will not be very accurate but together with the varying signal strength, it should be possible to find and recover the FISH if it is deemed necessary to do so.

14. Link budgets and bandwidth assessment was performed in section 3.3.7

15. The interference test has been conducted and was successful for both the optional frequency bands. The detailed report for this test may be found in the Software Appendix.

16. Clarification of details of system tests are currently under development as the integration phase is underway.

17. It is not very feasible to measure the friction on the line during any testing. This is because the friction is very low and the measuring devices available to the team are not accurate enough to detect any changes useful to the team's design. For such an analysis, the rig at Delta-Utec could be employed. However, for the project this is not planned to occur due to the budgetary and time constraints. If the outcome of the flight is a recommendation for perturbation and friction testing, the analysis of the friction will likely be considered.

18. The frequency risk has been shown to be minimal through the conduction of the interference test. The other risk values have been updated to reflect more realistic levels.

19. See 1.

20. See 15.

21. This will be coordinated with ESRANGE personnel well in advance of the launch week.



22. A simulated drop is included in the control algorithm. But the mechanics cannot be moved fast to allow for a 1 m drop. Therefore the FISH must be secured during that operation to avoid accidental impact during that test.

23. The setting of the CYPRES has been added to the countdown list.

24. Minor updates have occurred but picture log is still underway. The webpage updates were stalled as the team enquired about possible patents for the project.

25. The outreach competition is currently open, with the details available on the project website. Selection criteria were updated and detailed further following the CDR, with the inclusion of such measures as multiple age categories. For further details of the competition please refer to Section 6.3 and the Outreach Appendix.

4.4 Mid Term Review - MTR

Date: 28 August 2009

Location: BEXUS Room, IRV, Kiruna, SWEDEN

Participants:

a) Experimenters

Mikulas JANDAK

Mikael PERSSON

Jan SPEIDEL

Wrn Nawarat TERMTANASOMBAT

b) Review Board

Mark FITTOCK

Olle PERSSON

4.3.1 Recommendations of the MTR-Board:

1. The reel can move a bit within the structure so that it is possible that the linear actuator is not attached to the anti-reverse switch of the reel anymore. This requires fine-tuning.

2. Mounting on the gondola: It might be possible that we need longer bolts than ESRANGE can provide. We should consider ordering larger bolts.

3. Mikael proposed to use threadlock to secure all screws in the structure, this was OK with Olle.

4. The brake for the line guide may not be necessary, since the gearbox builds up a lot of force. It is almost not possible to turn the shaft by hand.



5. Suggested putting clamps of the reel steel wire on the metal steel plate so that more force can be used.
6. Suggested using crossbeams to improve stability of the insulation cover box.
7. There are at least four working days until the mechanics is ready. A major problem in the mechanics is that a shaft coupler has not arrived (rubber tubes being used as a temporary replacement for testing).
8. Find a way to access the CYPRES control unit to arm and disarm the parachute deployment mechanism and to see if it is active. Cut out a small piece of the side wall for that.
9. Put the motors in the thermal chamber, put heater on the motor. It is possible to wiggle the motor during ascent to prevent it from freezing. Put the camera in the vacuum chamber.
10. Offered the team a fit test at ESRANGE and to put the MAIN Payload on the gondola to see if there is enough space, as the E-link experiment might be above the experiment.
11. Permitted to deliver the experiment to ESRANGE one week later than originally required (now September 28 for reel.SMRT). This is conditional on the fit test and cutting the hole in the bottom of the gondola.
12. For the on-off switch, use a MIL connector and connect the pins so that they act as a bridge, connection can then also be used to externally power the FISH OR use a locking switch. The connector has to be attached to the MAIN Payload by a string so that it can't get lost.
13. Recovery: write instructions for recovery crew (cut of FISH, turn of CYPRES etc).
14. Sticker for the FISH: 'Return to ESRANGE if found'.
15. At least one side of the insulation of the MAIN Payload should be detachable so that the experiment can be accessed.

RESULT: MTR PASSED

4.3.2 Response to the Recommendations of the Review Board

1. This was fine tuned and changes to the switch were made such that it cannot become loose.
2. Bolts were supplied and implemented correctly.
3. Threadlock/ locktite was used.
4. The reason for the high gear forces was an error in the assembly of the gear and motor. Following the MTR, it was fixed and was able to move more easily. Thus, the brake was still implemented.



5. Not implemented.
6. Instead of crossbeams, Aluminium plates were implemented.
7. The shaft coupler arrived in time for further testing.
8. A side panel was cut out of the FISH enabling easier access to the CYPRES. This is depicted in Section 8.7.9.
9. Heaters were used on the motors and kept them within operational range.
10. This was conducted.
12. This suggestion was implemented using bright red boat keys to turn each battery on or off.
13. These were written and delivered in both English and Swedish to the crew. These instructions may be found in Section 8.7.9.
14. Sticker used and is hopefully effective.
15. Two panels are able to be taken off without taking off the others first.



4.5 Test Plan

Due to the complex and highly mechanical nature of the project, the testing of reel.SMRT needed to be rigorous. Flight in the stratosphere necessitates validation both of components, interfaces and system performance in thermal and low pressure environments. In this section, the original ntests and test plans for each subsystem are presented. Further information about each test, including the test objectives, procedure summary, location, conditions and required resources may be found in the individual subsystem appendices (Appendix 3,4 and 5).

Testing facilities utilised in the test plan include the thermal and vacuum chambers at IRF, which were secured for this project. Two tests were performed at ESRANGE to determine the EMC of the motors and the Zigbee pro communication modules with the E-Bass system.

Key integration tests for the system include that of the reel, motors and autonomous operation which were planned to be complete no later than the end of August, but were in fact conducted throughout September and early October until successful results were achieved after a number of design iterations. These tests ultimately confirmed full functionality of the system prior to flight.

4.5.1 Mechanical Subsystem Tests and Test Plan

As shown in Figure 4.1, the mechanical tests were planned from the end of May to the end of August, which left some time for contingencies, and indeed there were. The testing program first involved the testing of the strength of the central components such as the reel, the line, the line interface, the braking strength, and line guide. Then, as components of the prototype were built, they would be tested also. When the FISH was built, the insulation and interface to the line was verified. Then, as the mechanisms of the MAIN Payload were built, they were tested for strength, reliability, and functionality. The most basic tests were performed in the month of June as the prototype of the MAIN Payload started to take form, these include the strength of the structure and that of the line-guide.

Finally, once the entire system came together, advanced tests were performed on the functionality of the MAIN Payload's systems and on the FISH including its behaviour under free-fall conditions in the stratosphere. Additionally, some tests were planned on the aerodynamics of the FISH but time and resources did not allow for them. For more details on the specifications of the tests, refer to Appendix 5 for a complete table of the planned test cases and short reports on the results of the performed tests.

As mentioned in Section 5.4, some issues have delayed the construction of the mechanical hardware and consequently, the original test plans have been shifted in order to prioritize the use of the facilities of IRF for the construction. In Appendix



5.6, the results of the tests that have been done are present and those that have not been yet are left blank, the reader is encouraged to refer to that section for a better grasp of the status of the tests in the mechanical subsystem. . In a nutshell, the time and resources did not allow the completion of all planned tests. However, the most critical tests were performed to provide the assurance that the mechanical subsystem could perform the mission tasks within reasonable safety margin. These critical tests included the strength of all components, the holding strength of the line-guide, the resistance of the FISH to the drop braking impacts, the reliability of the parachute deployment, the reliability of the bail release and shutting mechanisms, and the reliability of the various operating actuators of the reel and line-guide mechanisms. The results can be summarized as follows:

- The strength of the line guide mechanism showed that the physical structure could easily support the loads and the geared motor alone could provide enough resistance to support the FISH for the ascent phase. The safety brake provided only additional security, but was shown not to be an absolutely necessary component.
- The strength tests of the MAIN Payload's structure showed that it was more than capable of handling the expected loading conditions in the vertical and horizontal axes. However, some weakness was identified and expected with respect to twisting loads, and hence, a recommendation followed to either provide an additional structural element (see Section 54) to absorb twisting loads or to assure that the screws are well tightened before flight and that the mass distribution of the electronics boxes are as symmetrical as possible.
- The bail release mechanism tests were performed multiple times because the first test showed that the selected servomotor was too weak to perform the task, and so did the second test of the re-selected servomotor. Finally the strongest servo available showed to be very reliable in releasing the bail under the load of the full FISH's mass.
- The anti-reverse switching mechanism was tested as well and showed very satisfactory behaviour in all tested conditions from room temperature to moderate subzero temperatures.
- The reeling system was tested repeatedly, both alone and within the full system tests (Section 4.5.1) and showed very satisfactory performance in terms of speed and smoothness of the reeling-in and reeling-down operations.
- The reeling mechanism was tested for lower temperatures which found that the spool thermally contracted in the outside temperature. This resulting in the line winding itself off the spool due to the reduced friction between these two devices. This problem was solved via rewinding the line



on the spool at the lower temperature, thus friction was maintained at the lower temperatures.

- The bail closing mechanism gave the most trouble. Initially, the block which was to trip the bail into closing showed to perform perfectly under no-load conditions, but when loads were applied to the line, the tripping was not able to fully close the bail which would cause it to re-open. A design modification was implemented to solve the problem, essentially extending the reach of the tripping block. However, when further tests were performed, the piece joining the bail to the reel's fork broke as it was made of high-strength plastic of some kind. Finally, the piece was custom machined at IRF to replace it. Moreover, some modifications were made to its design: the piece was made of forged steel to assure sufficient strength and it was extended downwards to facilitate the line in sliding into its final position in the pulley-like piece at the one end of the bail. The result was a much more reliable bail closing mechanism but a certain loss of smoothness of the reeling operations because the lowering of the one end of the bail caused some skipping when reeling in the line which ultimately resulted in a certain level of entanglement of the line on the reel's spool.
- Tests were performed to assure the reliability of the parachute release mechanism which showed after minor modifications that the parachute deployment was very reliable.
- The strength of the FISH's structure showed during tests to be sufficient to resist to impact of stopping the free-fall and also allowed for some weight reduction modifications prior to launch.
- Finally, the strength of the line was tested in static conditions to prove that it was sufficiently strong but the stopping force (applied by the reel's brake) had to be reduced compared to what was initially planned, extending the stopping distance and hence reducing the possible drop distance. During dynamic tests of the stopping impact, a bungee cord was added to the end of the line to smoothen the impact force such to limit the likelihood of the line to break.

In summary, the tests that were performed verified all major operational requirements. They did lead to numerous design changes, but all were minimal and easy to implement on short notice, within the final few weeks of preparations for the launch. Thus all mechanical tests strength tests were conducted as pasted prior to launch. The critical thermal tests were completed but no pressure test were complete prior to launch. This was due to due to limited access to the thermal and pressure chambers prior to launch along with the large delays in the development of the project.

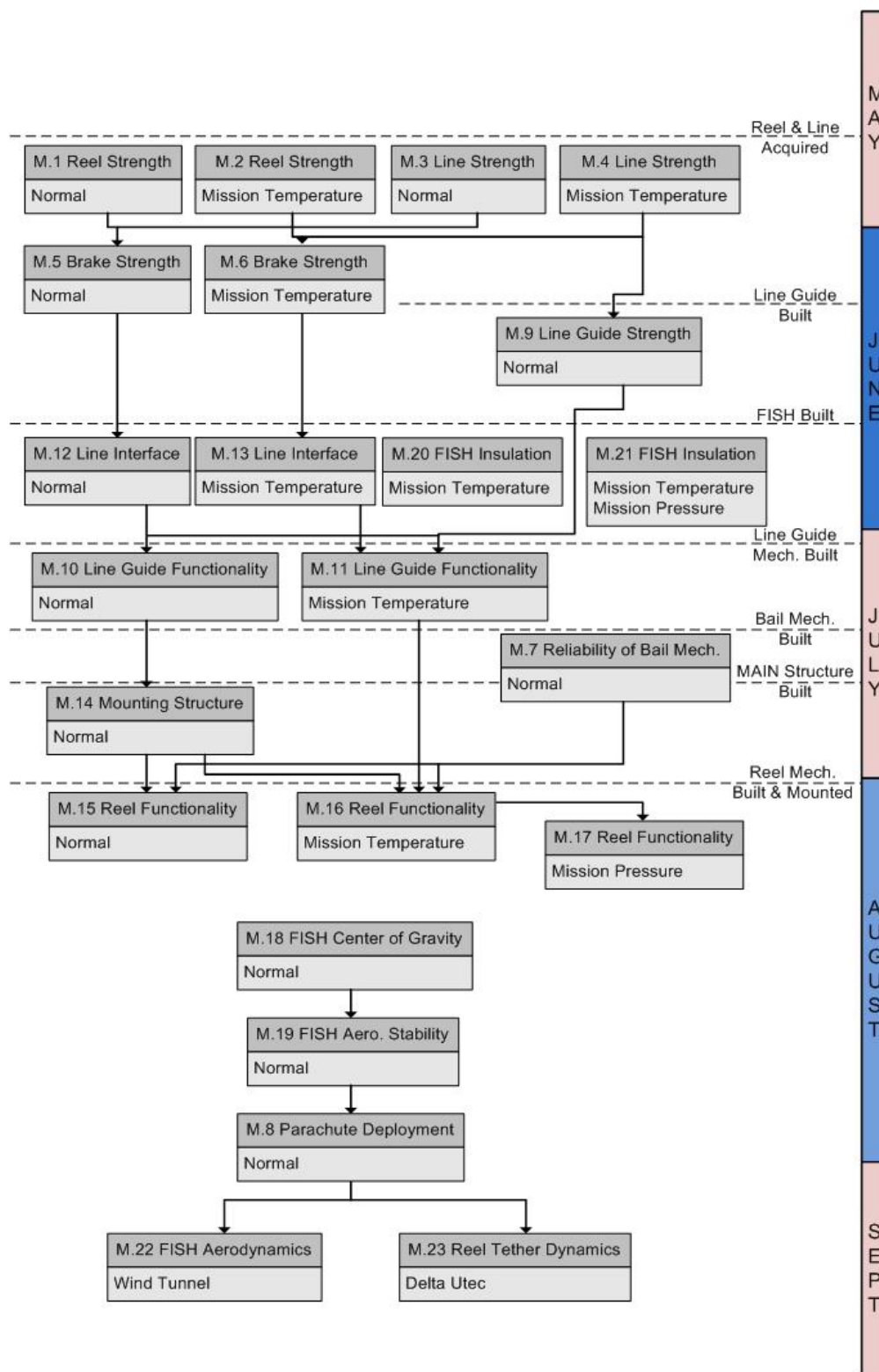


Figure 4.1 Original Mechanical Test Timeline. Tests M.22 and M.23 were not performed due to time and resource constraints.

4.5.2 Electrical Subsystem Tests and Test Plan

Figure 4.2 shows different tests, which were performed after the initial design phase. The bulk of the tests are to be performed in July after the PCB is populated. The figure shows dependencies between different tests. The most fundamental tests were performed at the beginning with more complex tests following them. Some of these tests were conditional for particular hardware to be used in the final design. For example the magnetic compass test may be replaced by another test, which was to calibrate the alignment between the FISH and the MAIN Payload. Nonetheless, almost all of these tests were to be performed. Figure 4.3 shows tests with respect to time and also to other subsystems. These tests although show separately may be combined with others in order to use more effectively the recourses (pressure chamber, temperature chamber).

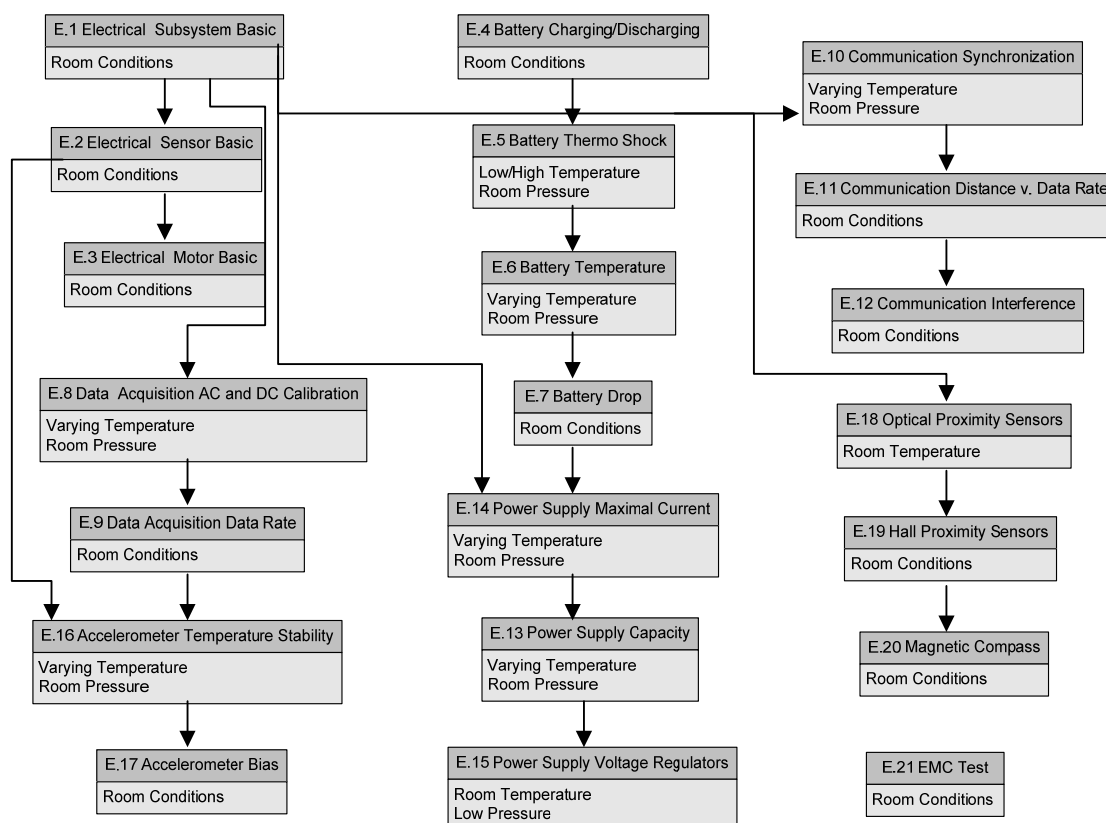


Figure 4.2 Original Electrical Tests 1 of 2

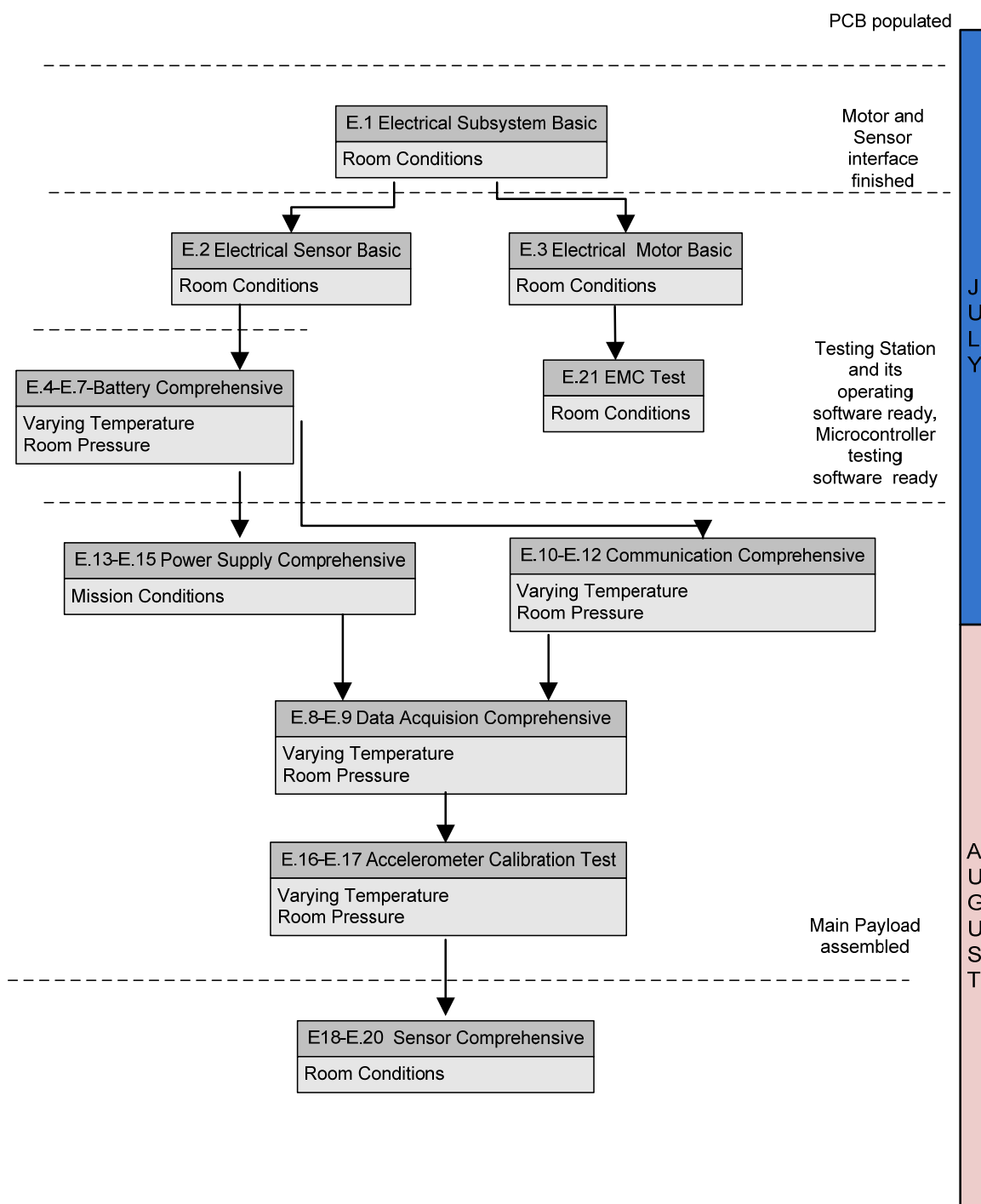


Figure 4.3 Original Electrical Tests 2 of 2



4.5.2.1 Critical Test Summaries

Test E1: Electrical Subsystem Basic

Purpose: to evaluate the proper function of the hardware

Equipment used: Regulated Power Supply, oscilloscope, multimeters

Phase A: Power System Distribution PCB

The PCB complied to the following:

- a) The voltage across 5V regulator measured after the diode for redundancy capabilities were between 5.36V and 4.85V for the output current of 0A to 1.9A. All 5V devices are tolerant to such voltage variations for proper functionality.
- b) The voltage across 3V regulator measured after the diode was in between 3.45V and 3.01V for the current between 0A and 1.7A. All 3V devices are tolerant to such voltage variations.
- c) The 10V regulators were capable to deliver 1.8A which indicates 80% margin for the RC servos.
- d) The 12V regulators were capable to deliver 1.8A which indicates 400% margin for the linear motor.
- e) All voltages were measured even when only one battery was present.
- f) The monitoring circuit was tested by applying different address on the multiplexer and the result was that all voltages across the batteries were monitored through the isolation barrier.

Based on this test the Power Supply Distribution PCB was found to be fully tested and ready for assembling. The tests which still have to be performed are E15-E16 where the thermo tests are to be perform.

Phase B: Motion Control PCB

The PCB complied to the following:

- a) The optoisolation barrer between the brushless controllers and the microcontroller was tested. Both analog and digital signal could be put through.
- b) The linear motor controller could be used for adjusting the position of the switch.



- c) The heaters were tested and they are capable of delivering at least 2A at 24V. However, for this rating the heatsink must be added since the temperature of the case was steadily increasing beyond the safe zone for the power switches.

The PCB did not comply to the following:

- a) Brushles controllers were not working. The troubleshooting of this part may be difficult; hence; the decision to replace them by industrial brusheless controllers were made.
- b) RC Servo did not operate properly. This test showed a flaw in the design. The MAX3088 could not be used for the intended function.

Result: The PCB was be redesigned; however; the parts which were successfully tested were used for testing during assembly.

Phase C: Power Microcontroller PCB

The PCB complied to the following:

- a) The appropriate voltages were measured at desired pads.

The PCB did not comply with the following:

- a) The conductive test was performed between the pins and the pads. The

Conduction was measured between pins 53 and 54. New microcontroller is to be bought and the old one either replace or populate again.

- b) The switch for the activating the bootloader was placed on the wrong pin; however; this will not affect the performance during the mission since this is use only during programming so external switch has to be added to the PCB.

E21 EMC Test

The radio at low waves was used to measure the potential interference coming from the power distribution box; however; no significant interference was measured. This indicates no potential problem with EMC due to the switching power supply.



Due to the time constraints in August and September only low vacuum tests and low temperature tests were performed. All comprehensive tests (data acquisition, sensor comprehensive) were skipped.

4.5.3 Software Subsystem Tests and Test Plan

During the development of the software subsystem it was possible to test three subparts independently. These parts were: the ground station, sensors, and actuators. Also it was not necessary to do a lot of testing in vacuum chambers or in varying temperature. Only when it came to moving parts (actuators) and a test of the whole setup in mission conditions was this necessary.

The interface between the microcontrollers and the sensors on board the MAIN Payload and the FISH were tested independently. The main task was to verify the correct implementation of the various bus protocols. For example the temperature sensors are connected via a I2C compatible bus system, whereas the accelerometers use a proprietary serial bus system.

Since the electronic circuit boards for the experiment were not completed by the time the software testing started in June, vital parts of the electronics were built up and connected to the evaluation boards using prototyping boards and standard electronic components. It was therefore possible to develop the software testing independently from the pace of the Electrical Subsystem.

4.5.3.1 MAIN payload Sensors, Actuator and Component Individual Tests

- The I2C temperature sensors were tested to read out from the microcontroller.
- An external digital to analogue converter based on the SPI protocol was connected to the microcontroller and its performance was as expected
- The digital hall sensor was tested to work with microcontroller both interrupt driven and sequential readout.
- The servos that open the bail were tested with microcontroller to move it.
- SD card storage was tested. The microcontroller could write the data into the SD card at high rate but the microcontroller could read or write to the SD card just only one file in a time.
- Motor movement was tested with the microcontroller, digital to analogue converter and motor driving circuit. The motor turning speed and turning direction could be controlled from the microcontroller.
- The proximity sensors were tested using analogue output. It was found out that, the output signal contained a lot of noise especially from the far distance. Many of the proximity sensors used for redundancy caused some interference between themselves, so the usage of it them was limited to only one sensor in a time. Also because of the high noise level, the output of proximity sensor was



designed to connect to microcontroller via Schmitt-trigger to get the digital input to give only the signal that the FISH is present or absent.

- The linear motor was tested to be moved by the command from microcontroller via electrical H-bridge circuit in motion board from electrical subsystem.
- A 24 bit analogue to digital converter on FISH has been tested by input adjustable voltage from the power supply to the component. The digital output read by microcontroller was changing according to the input voltage. During the test, it was found that the connection to this component on the FISH electrical board was not correct. Modifications to the board were required to have the component in working order.

At the last stage of development, it was found that the microcontroller from the electrical subsystem was not working properly. So, the evaluation board used in the tests was implemented into the design, with a prototyping board on top of it.

4.5.3.2 Software system level tests

- The test sensor data packets were propagated from the FISH via the MAIN Payload to the ground station by means of the communication protocol. There were some problems in the MAIN Payload such that the processor time was not enough to receive and send the data at the same time. So, the command structure was changed to have a termination time of the high data rate mode, the detailed communication protocol can be found in Appendix 4. The overall protocol was working fine in the test. The detailed test report can also be found in Appendix 4.
- Ground station software was tested for its ability to control the experiment by sending a command to move the actuators and change the data rate mode. The actuators could move according to the command, and the data rate was changed according to the command.
- The bail opening and closing mechanism was tested without the electrical power and the motion board. The test was instead conducted by using power supplies and the microcontroller board. The command was sent from the ground station to tell the microcontroller to open the bail by moving the bail position to stop at the opening position, move the servo to open the bail, and then move the bail to the closing position. The mechanism was working fine without the load at the end of the line. However, with the heavy load that simulated the FISH weight, the small servo could not produce enough torque to open the bail. This lead to a changing of the servo component to new and stronger one.
- The SD card sensor storage with mock up data was tested in both the FISH and the MAIN Payload with the communication protocol for the data buffer. The data from the FISH and the MAIN Payload could be stored on the local SD card. The data from the FISH could also be stored on the MAIN payload SD

card. Therefore the MAIN payload and the FISH could use the SD as a data buffer for sending in high data rate mode.

- Data propagation was tested with real data from sensors both from the FISH and the MAIN Payload to ground station. (Before the last change in the data packet).

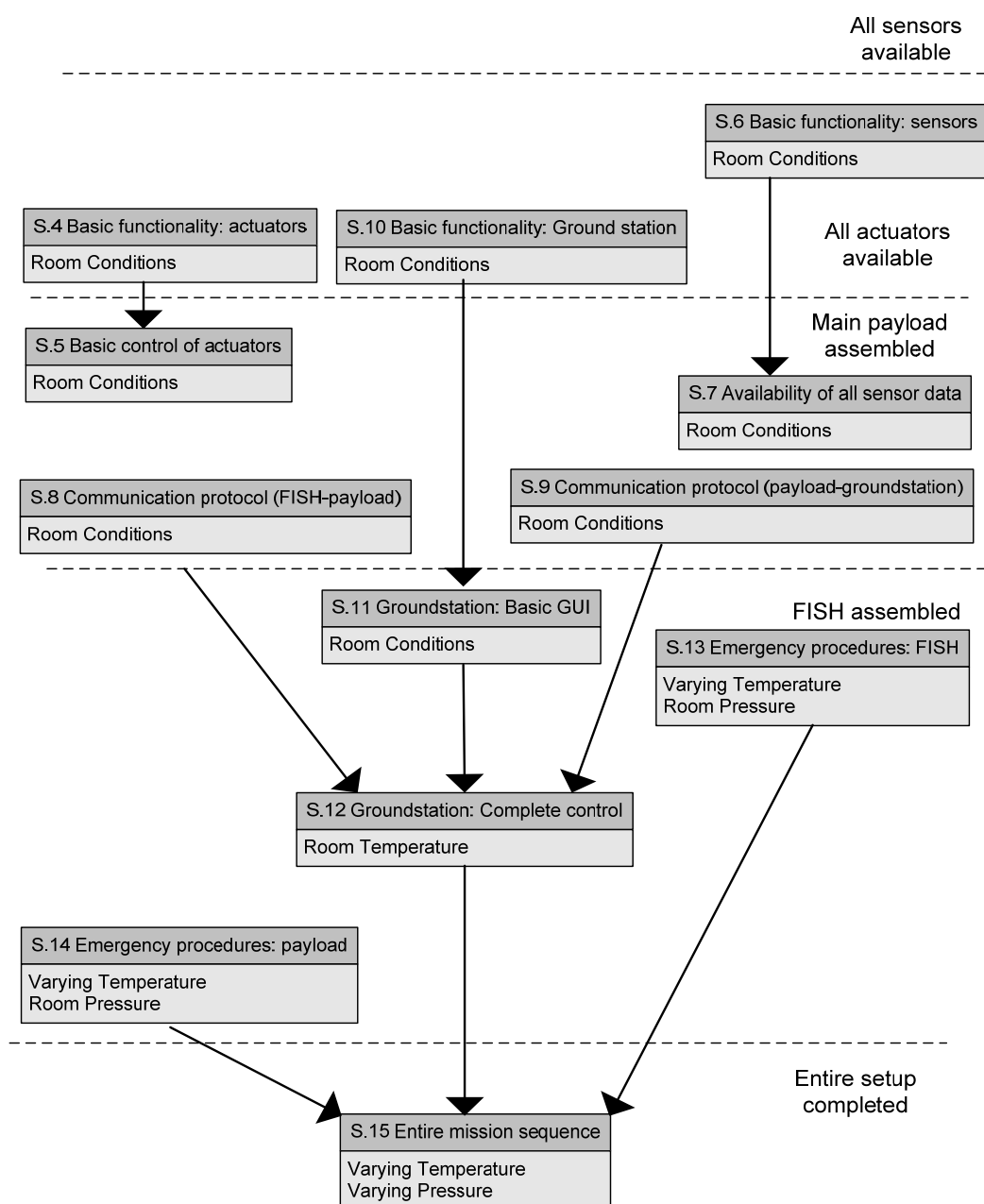


Figure 4.4 Original Software Tests



4.5.4 System Level Tests and Test Plan

There were three key system level tests that were performed in order to verify the reel.SMRT system and its requirements. These tests were conducted in late September in Kiruna as well as during the first half of the launch campaign.

4.5.4.1 Slow Reel Mode System Test

The slow reel mode test was conducted to ensure that all systems operated in all anticipated scenarios of the slow reel mode of the system. That is, the experimental hardware and software was be run through all situations (including emergencies) except for the drop mode sequences: for this test, the bail remained closed throughout the test procedure.

This test was used to verify the emergency software procedures and hardware interfaces of the slow reel mode and its emergency sequences. To perform the test, the MAIN Payload was hung on the crane within the ESRANGE cathedral building. A first run of the test was performed with the team members in location and observing the performance of the system.

The second run of the test was performed with the operators out of visual sight of the experiment, such that they had to run diagnostics through the MAIN Payload IP camera. This test was successful, but was run using a dead weight instead of the actual FISH on the line; the FISH was sat on a bench in the cathedral for the xbee communications testing.

4.5.4.2 Mission Sequence System Test

The MAIN Payload was placed on a bench with the FISH sitting on the ground beneath the MAIN Payload, within communications distance.

The reel.SMRT experiment was be run through the entire nominal mission sequence from the ground station, including slow reel and drop modes. This test included locking and unlocking the line guide. During this time, the battery levels and power consumption were monitored and the software communications and data storage algorithms and protocols were checked and found to operate correctly. Once the FISH was in working order, this test was run a second time, with all systems found to be operational.

4.5.4.3 Drop Mode Test for MAIN Payload System Test

The drop mode test was conducted to ensure that all MAIN Payload systems operated in all anticipated scenarios of the drop mode of the system. That is, the experimental hardware and software were be run through all situations (including emergencies). However, for this test a dead weight of the equivalent mass was used in the place of the FISH to protect the FISH hardware in case of any test failure. This test also acted to verify that the bail mechanism could close at the unreeling speeds anticipated during the flight. This was a critical test for the flight

and if the bail could not close the drop distance would have needed to be shortened in the flight plan.

Countless drop tests were performed during the launch week. The methodology essentially consisted of raising the MAIN payload on a crane to about 7 m and 12 m at the cathedral and MAXUS tower of ESRANGE, respectively. Tests were ultimately successful with reduced weights, at reduced dropping distances.

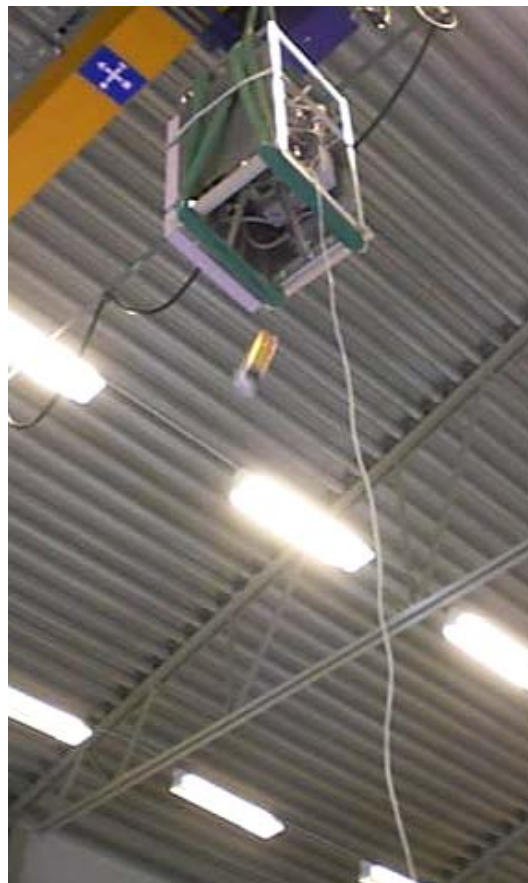


Figure 4.5 Drop test video snapshot. A beer can is used here as a light mass on the end of the line in initial system testing.

Several difficulties were encountered were mitigated by implementing the necessary design solutions in rapid succession. Mainly, it was determined that the setting of the brake on the reel and the precise positioning of the mechanisms



were very critical to the success of the drop functionality. An image of a drop test with a light mass on the line is shown in Figure 4.5.

A summary of the conclusions of these tests follows:

- The bungee cord on the end of the line was a necessary addition to the system as the line tended to break very often otherwise in the 12 m drop tower when the full weight of the FISH was applied. With this addition, the stability of the FISH hanging below the MAIN payload would suffer to some extent, but flight data finally showed that the dangling was more than acceptable, with negligible bouncing visible on the video feed.
- The entanglement of the line on the reel's spool caused some problems in achieving a good drop. This was a consequence of a design modification to the reel system which was also necessary and hence, this was a necessary evil that would limit the possible number of drops performed during the flight to two or three. Prior to the launch, the line was hand-wound on in an attempt to ensure smoothness and snag free initial drop.
- The current limitation that was inherent to most of our tests on power supplies was a critical factor in the bail closing operation as it required a high stall torque on the reel motor. This showed to be a non-issue when operating with the battery pack, but it was nevertheless interesting to find that the motors could easily draw 6 to 10 A of current (under 24 V) during the bail closing operation.
- Several drop tests were unsuccessful at some point, and it was found that the position of the servomotor mounting had become loose and was blocking the bail from closing. It was then recommended and added to the pre-launch checklist to secure the position of the servomotor mounting and this was implemented for the flight. Additionally, if the time of drop was set to be too short from the ground station (approximately 600ms or less) then the bail would not close. This because the reel would not be given enough time to spin around in a full revolution, which was required for the bail arm to impact the steel block and close.
- Drop tests were conducted in the MAXUS drop tower under subzero conditions. It was found that under these cold temperatures, the reel thermally contracted sufficiently for the line to run off the reel. This was not evident in the temperature chamber testing, as there was no load on the reel during that test. To mitigate this thermal contraction, the line was pulled off the reel and shortened to 70 m. This meant that in the scenario that it did run off the reel during flight, it shouldn't gain enough speed to snap the line off the reel. The line was also rewound back onto the reel at this cold temperature. These changes were proven to be effective during the flight,



as the line did not spool off the reel during ascent or even once the line guide was unlocked.

- A drop test with the full FISH weight was performed in the MAXUS drop tower during launch week, with success. This test was recorded on video and demonstrated functionality of the MAIN Payload system.
- From these numerous drop tests, a greater understanding of the system performance was achieved. This allowed for a proper understand of system diagnostics which enabled the diagnostics checklist to be written for the flight operations. This may be found in Section 8.2.



5 PROJECT PLANNING

5.1 WBS – Work Breakdown Structure

The work breakdown structure has been an important part of the project monitoring and evaluation. It gives others looking at the project a brief overview of the work involved and for the project manager a fast method of evaluating which parts of the project have been successfully completed. reel.SMART's original WBS (see Figure 5.1) was created from a team survey also used for the Gantt (see Section 5.2.2 and Appendix 2.2).



reel.SMRT

1 Project Management

1.1 Team Management

- 1.1.1 Task Delegation
- 1.1.2 Deque Negotiation
- 1.1.3 Project Tracking
- 1.1.4 Budget Management

1.2 Documentation

- 1.2.1 REUS Application
- 1.2.2 PDR
- 1.2.3 CDR
- 1.2.4 I/MR
- 1.2.5 EPR
- 1.2.6 Final Report

1.3 Sponsorship

- 1.3.1 Acquisition of Funding
- 1.3.2 Sponsor Support

1.4 Operations Management

- 1.4.1 Launch Site Contact
- 1.4.2 Launch Campaign Management
- 1.4.3 Flight Management

2 Mechanical

2.1 Design

- 2.1.1 Mounting Design
- 2.1.2 Reel Design
- 2.1.3 Live Guide Design
- 2.1.4 FISH Design
- 2.1.5 Live Design

2.2 Component Acquisition

- 2.2.1 Component Ordering
- 2.2.2 Component Storage

2.3 Construction

- 2.3.1 Mounting Construction
- 2.3.2 Reel Construction
- 2.3.3 Live Guide Construction
- 2.3.4 FISH Construction
- 2.3.5 Live Construction
- 2.3.6 Assembly Construction

2.4 Testing

- 2.4.1 Strength Testing
- 2.4.2 Reliability Testing
- 2.4.3 Functionality Testing
- 2.4.4 Interface Testing
- 2.4.5 OVG Testing
- 2.4.6 Aero/Thermo Testing
- 2.4.7 Thermal Testing

2.5 Simulator Software

- 2.5.1 Construct Simulator
- 2.5.2 Simulator Upgrade

3 Electrical

3.1 Design

- 2.1.1 FISH Design
- 2.2.2 MAIN Payload Design
- 2.2.3 Power Design
- 2.2.4 Communication Design

3.2 Component Acquisition

- 2.2.1 Component Ordering
- 2.2.2 Component Storage

3.3 Construction

- 2.1.1 FISH Construction
- 2.2.2 MAIN Payload Construction
- 2.2.3 Power System Construction

3.4 Testing

- 2.4.1 Sensor Testing
- 2.4.2 Communication Testing
- 2.4.3 Electromechanical Testing
- 2.4.4 EMC Testing
- 2.4.5 Power Testing

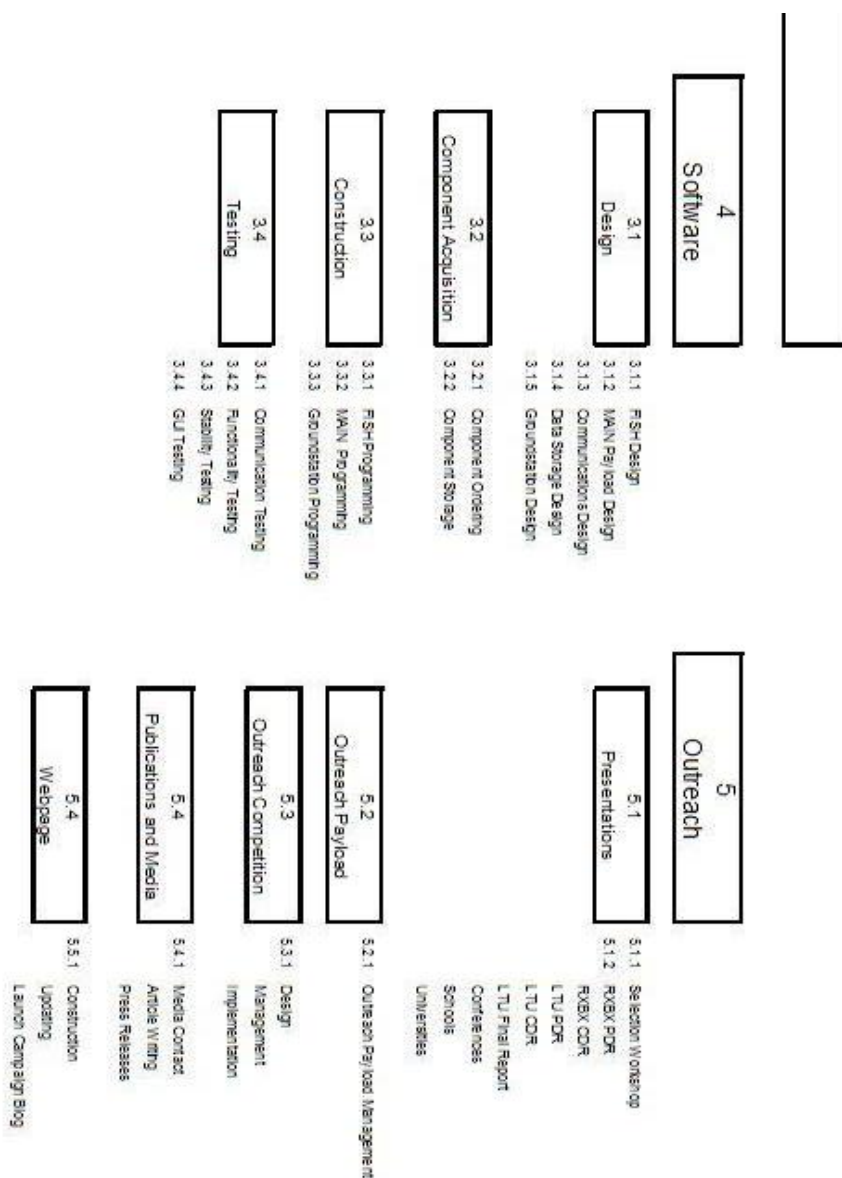


Figure 5.1 WBS



5.2 Management

5.2.1 Team Composition

The reel.SMRT Project team is comprised of seven students from the 'Erasmus Mundus Joint European Master in Space Science and Technology', or 'SpaceMaster'. There is one Round 3 member, who started the project in his second year of the programme and six Round 4 members, who started the project in their first year of the program and then studied at LTU in Kiruna, Sweden between February and June 2009. More information about the responsibilities and backgrounds of each member are presented in Section 1.5.

Following the PDR, Jürgen Leitner, of Software, became an assistant member rather than a full member of the team, due to how the multiple commitments he had for his thesis prevented him from being able to fully contribute to the project as a full member. Juxi continued to contribute to the team as the webmaster as well as obtaining many of the team's key sponsors. Prior to the MTR, Juxi left the team due to conflicting commitments hindering his contributions to the team. He has agreed to continue to run the webpage for the project and maintain his original financial contribution to the team as agreed when he was a member.

Following the CDR, Mark Fittock, of Outreach, left the team due to conflicting commitments. Mark has continued his involvement in the team in a mentoring role and similarly to Juxi has maintained his financial commitment to the project. Since this time, Katherine, the Project Manager, has assumed responsibility for the project's outreach goals and tasks.

Each member of the reel.SMRT team originally located in Kiruna is expected to do equal amounts of work to achieve the best outcome for the project. The workload required is dictated by task allocation and thus is outcome driven (tasks achieved) rather than time driven (hours per week). The detailed taskings for each member were established immediately following the ESW, are revised after each Design Review and are monitored both by the Subsystem Managers and the Project Manager. Within each subsystem, the Subsystem Manager is responsible to the Project Manager for the implementation of their tasks. This means that the Subsystem Managers delegate tasks within their subsystem and ensure their timely completion as well as keep their overseas counterparts up to date. The team is structured so that the Subsystem Managers and the Project Manager were all located in Kiruna during the semester, for ease of communication and control.

The interface definitions between each subsystem and thus subsystem responsibilities may be obtained from the Section 3.4.2.



5.2.2 Project Planning Methodology

Unique management challenges are present in this project. The team, being composed of originally nine members (eight from the CDR onwards, seven from the MTR onwards) spread between four and at one stage more than seven separate countries over the course of the project, all with a variety of backgrounds and not previously well acquainted with one another, posed potentially significant barriers to communication and collaboration. To meet such challenges, a comprehensive project management plan was implemented with a single member as the dedicated project manager. This enables more thorough time planning and interface supervision, in addition to greater command and control capability over the team.

At the commencement of the project it was made clear to each member their individual responsibilities as a group member for this project, the management structure and the level of workload involved. An email list, a file sharing website and a milestone/task page on the 'basecamp' website was established through which communication of all project information has been made. The DLR sharepoint site was also established as the key file sharing site for the team, enabling more efficient compilation of design and administrative documentation. This has ensured that all members of the team are aware of the developments within each subsystem design and may access and add to these documents in an efficient manner.

The initial taskings to the subsystems were as follows, in order of priority: subsystem task breakdowns and timelines, subsystem requirements and initial budgets, inter-subsystem interface definitions, initial design, risk analysis, test plan and then the more advanced preliminary design analysis. Such staggered taskings in the five weeks to PDR enabled more effective work planning and workload distribution over this period.

For the period up until the end of the CDR, bi-weekly meetings occurred for the six members present in Kiruna, with additional weekly meetings planned for the entire team present over the Skype conference call system. During these meetings, each member presented the work since the last meeting and in doing so the team members pushed each other to work harder and maintain the pace of the design progress.

Between the CDR and the MTR, team members were spread over seven different countries, some with internships and others travelling back to their homes. To ensure ongoing communications and continued progress, the team each emailed weekly updates at a designated time to the rest of the team. This method seemed to be a success, with progress continuing over the summer and control of the budget, design interfaces and resources being maintained. Since mid-August, four team members (at least one from each subsystem) have been present in Kiruna and working on the project. During the end of August and September, these members worked full-time on the reel.SMRT system.



Between the MTR and the launch week, all team members worked diligently on the project. The extensive testing required was not completed in time for launch week, as many unforeseen issues arose during the integration of subsystems. This in many instances required the ordering of new components and additional testing or design iterations. For some systems, team member had to coordinate these design iterations between countries over Skype, and had to ship new components. Consequently, the budget was significantly overstretched and the original schedule was unable to be adhered to. Nevertheless, due to hard work and perseverance of the team, and valuable assistance from both ESRANGE personnel and LTU staff, the team were able to successful complete all required tests and thus fly on BEXUS-9. The team, as a result of these efforts, learned an incredible amount.

5.2.2.1 Interface Definition

Management involved responsibility for system integration, that is, the collaboration of all the subsystems to produce the final design product. Initially high level requirements and constraints of the project were developed, including budgets to guide the development of each subsystem. This presented a 'top down' approach to the design.

Integration in the design phase involved setting requirements, defining subsystem interfaces, whilst integration in the construction phase required thorough testing of all interfaces. For this design phase B, each subsystem was tasked with setting strict requirements that defined the constraints on their designs from other subsystems. An Interface Control Document was established, where subsystems together defined their interfaces and the responsibilities of members involved in these interfaces. Additionally, following the PDR a 'Requirements Verification Table' was established to assist in ensuring that each of the projects requirements shall be met. Both of these documents may be found in Appendix 1. Consequently, the onus was placed on each subsystem to ensure that the performance of their particular subsystem was in compliance with the functional and technical requirements.

Since the CDR, the interface definitions became of paramount importance. Members constructing the hardware and software around the globe were stringent in maintaining communications to ensure clear understandings of the interfaces. The interface tests were planned for completion in late August and early September when the hardware, and relevant members, are present in Kiruna. However, such time constraints and challenges in achieving these led to many members working on both the Electrical and Software subsystems to achieve successful test results.

5.3 Resource Estimation

Estimation of the resources for the reel.SMART project necessitated an investigation into a number of factors. These included, in addition to the individual



team members: finances, time, components, access to facilities for testing and construction as well as academic and financial support. In this section, each of these factors shall be addressed. The estimation of required amount of resources changed over the course of the project with design iterations, better understanding of components required and test results. The initial resource estimation for this project was sufficient until the MTR. However, between the MTR and launch week, many more resources were required than were anticipated.

5.3.1 Mission Finance Budget

The reel.SMART project finance budget depended on the size, complexity and scheduling of the project. It also was a function of risk mitigation levels, component quality and proficiency of team members in locating the optimal products. The project budget was originally capped by the individual members willingness and ability to pay over a certain threshold level for the project, which may vary for each member but must be set to an equal contribution across all members. Within this framework the aim was to minimise all costs, where possible, without compromising the quality of the design or the ability to meet the objectives.

The prediction of the total budget was a complex process critical to determining the quality and feasibility of the design, and as such was also critical to the development process. It has undergone multiple iterations over the project cycle and was been closely monitored in an attempt to ensure that the project does not exceed its means. Such an activity has been particularly important for this project, as it has multiple members spread internationally, particularly over the June – August period, when members were working in over seven different countries and also in different time zones.

The project budget was based on information gathered and recorded systematically to allow for accurate estimates of cost. The cost estimating method employed was that of 'Detailed Bottom-up Estimating'. This involved identification and specification of costs from the lower level elements that make up the system (35). This concerned the establishment of subsystem budgets that were integrated into an overall system budget. The project budget was also further divided into cost groups within each subsystem: components and tests. Any component that had the possibility for sponsorship was also identified and labelled to be addressed by the Project Manager.

The cost estimation contributed to key design decisions, such as the quality of components. Such dependencies on funding incurred delay in the finalisation of designs and the schematics, as well as ordering lag time. To minimise this and to reduce the total budget, sponsors and supporting organisations were approached from the commencement of the project to ensure maintenance of design momentum and more accurate cost estimation. To facilitate sufficient reserves for subsystems to purchase the necessary components, a joint bank account for the team was established. By each team member transferring in their contribution, as



well as the sponsorship money deposited, pre-approved purchases were able to be made in a reasonably timely manner.

In the short time following the PDR, when the team realised that the budget of the project was beyond their means, designs were heavily investigated to look into how to make the system more cost-efficient whilst still achieving the aim. However, with the offer from ESA for sponsorship to the value of 3000 € and by Olle Persson from ESRANGE organising sponsorship from CYPRES for a CYPRES unit and the parachute for the team, the situation was resolved and the project was even able to be improved beyond the original designs. Between the PDR and CDR, the team also obtained an additional sponsorship of 1250 € from a number of companies. Such funding not only enabled the team to realise their design, but also to maximise the scientific output through such activity as further accelerometer calibration and testing of components.

Following the CDR, the required budget for the components was increased due to design changes necessitated by preliminary tests as well as unforeseen additional costs such as international shipping and additional taxes. Throughout the ordering phase of June, July, and August, the budget was rigorously monitored to ensure that the team did not exceed their means. As such, the additional costs were ultimately covered by the increase in sponsorship rigorously sought for and eventually obtained over the same time period, as well as cost-savings within both outreach and the mechanical FISH design.

At the MTR, the team was on-budget almost exactly, with required team member individual contributions calculated to be at 270 €, just below the 300 € cap set. Therefore, the budget at MTR was within the project requirement Req.O.11, which was the difference between funding and the project budget shall not exceed 4000 euro, as based on the ability of team members to pay.

However, between the MTR and launch week the system was fully integrated and so finally underwent the requisite system testing, with resulting design iterations as needed. These tests led to destruction of some key components, which were tested to failure. These last minute changes meant that many additional components had to be purchased at high expense and express shipping costs. For critical components deemed to be at risk of breakage during further tests, spares were ordered so that in such an event the system could still fly. Furthermore, during launch week testing, the MAIN Payload batteries became critically discharged, requiring new batteries to be purchased at high expense. Therefore, between the MTR and launch week the budget for the reel.SMRT project was significantly exceeded.

Due to this, additional sponsorship was sought out. The sponsors Daiwa, Platil Fishing Lines and Modern Fishing donated their components for no cost, rather than the 50% discount originally pledged. LTU also has offered the team an



additional 5000 sek (approximately 500 €) to help cover costs. In return, the reel.SMRT team would donate to LTU all of the components purchased with the ESA and LTU funding. This offer was under discussion with LTU at the time of writing. Furthermore, the team has compiled the components with potential resale value that were not purchased by ESA or LTU funding. These components are listed in Appendix 2. It is anticipated that these components may provide up to 400 € of funding for the team, although this is not guaranteed and they have not yet been put on the market (and therefore not accounted for in the budget). As a result of this funding and the aforementioned expenditure, the level of funding required to be covered personally by the team members is 6615 €. Not all team members will pay this due to personal financial constraints, however, ideally this would be split 8 ways, requiring 830 € expenditure per team member.

The final budget for the reel.SMRT Project is summarised and listed in Table 20. The value of 14350 € is the value for the project components 'off-the-shelf', that is, not including the discounts received. The value of 12165 € was the amount the team had to cover with monetary sponsorship and their own contributions. The more detailed subsystem cost budgets are listed in Appendix 2.1.

reel.SMRT Budget Summary at FINAL SED				
TOTAL RRP of PROJECT COMPONENTS			€	14350
Discounts (approx.)	CYPRES Unit	1	1200	1200
	Parachute	1	120	120
	Line	1	50	50
	Swivels	3	5	15
	IMU	1	400	400
	Reel	1	400	400
TOTAL BUDGET FOR TEAM TO COVER:				12165
Monetary Support	ESA	1	3000	3000
	GCS	1	300	300
	RUAG Aerospace Austria GmbH	1	800	800
	Sylvia Meinhart	1	150	150
	Juxi Leitner	1	300	300
	LTU	1	500	1000
TOTAL BUDGET AFTER SPONSORSHIP:				6615
Resulting Contribution of Team Members (per member contribution)		8		830

Table 20 reel.SMRT Budget Summary at time of writing



5.3.2 Time schedule of the Experiment Preparation

A Gantt chart was implemented for monitoring the progress of the project because it enabled a direct correlation of tasks with the duration of time, milestone and critical task amelioration, flexible time units for future tasks, and a visual representation for quick assessments of the project's progress. This has been particularly important for the project, as it necessitated fast development in the initial stages, and continued to require maintenance of momentum over the entire project, including the time up until the final report is submitted. Each subsystem originally set their own timelines and continued to update it as the project progressed, with the Project Manager overseeing the progress relative to the chart. By each subsystem setting their own tasks, they were aware of deadlines and pushed themselves to achieve their tasks. The Gantt chart at MTR is appended to this document in Appendix 2.2. Following the MTR a Gantt chart was not used closely as all members were in Kiruna working tirelessly on the project. Rather, a list of desired functionalities to be achieved, in order of priority, was established and posted where all team members could see it, so that these milestones could be checked off as soon as they were achieved. Visual recognition of this progress despite the challenges helped to keep the team spirit high.

The approach taken to the time schedule of the mission and experiment preparation was that of a high output from the beginning, with the aim to achieve the ever-elusive 'flat' effort versus time curve over the project phases. This approach was particularly necessary due to the many validation tests required for the mission. The rationale was that if all tests were on schedule and produced favourable results, then the ideal situation of the testing phase being complete with a flight ready model well ahead of September should occur. However, due to the many components that had to be ordered and the possibility of the necessity for re-designs following unfavourable tests and reviews, or unforeseen member time availability, a 'buffer' period was set from the middle of July until the middle August. This time comprised the 'summer break' for the members of this project and so any additional overflow work was intended to be completed in this period, if required.

In fact, due to delays in being able to order components due to additional budgetary trade-offs, delays in shipping of significant items (specifically the reel which took over two months to arrive), additional exams and level of work required in university subjects and theses and redesigns following the PDR the project was already behind the original ambitious schedule at CDR.

Consequently, the team was working consistently through the time since CDR. The Mechanical Subsystem undertook most of their construction immediately following the CDR, with the FISH building phase completed and the key parts of the MAIN Payload being constructed by late June in Kiruna. The electrical PCBs



for both the FISH and the MAIN Payload were designed in late June and early July, between the Czech Republic and Finland, with the designs being reviewed by third parties such as colleagues and university staff before being sent off for manufacture. Software continued to work on their writing and testing of their codes throughout the summer on the evaluation boards in both Thailand and Germany. The system integration and testing is being conducted in late August and early September, full-time in Kiruna by four members of the team.

Therefore, whilst the team thought they were working at their maximum throughout the project phases, this effort level was never permitted to reduce, due to the work workload being consistently high throughout the project phases!

To alleviate the workload, additional team members were sought out in June and July for the electrical subsystem. However, as the team was spread internationally, this was not possible to coordinate properly. Fortunately the brother of one of our electrical members was able to assist in the construction and population of the electrical PCBs, which aided the project.

The mission phases and milestones of the project are listed as follows:

Phase A: Feasibility Phase

- October 2008 Proposal Submission
- February 2009 Experiment Selection Workshop

Phase B: Preliminary Design Study Phase

Phase C: Detailed Definition Phase

- March 15 PDR Due (ESA)
- March 22-28 PDR Workshop and Presentation (ESA)
- April 1-7 PDR deadline (IRV)

Phase D: Production and Qualification Phase

- June 2009 CDR (ESA and IRV)
- Mechanical construction and tests complete

Begin Original 'Buffer' Period

- July: Software construction and internal tests complete
Electrical PCBs designed and reviewed
Individual Subsystem tests and construction complete
- Mid-August 2009 MTR (ESA)
Integration of modules commences - all subsystems in Kiruna
- Flight Readiness Review

End Original 'Buffer' Period

- Late September 2009 Delivery of Experiment Flight Hardware (ESA)

Phase E: Launch and Operation

- 2 October Launch Campaign (ESA)
- Mid October update sponsors and FISHy Design Competition Winners



- Mid-late October Search for the FISH (two expeditions)

Phase F: Post flight analysis and Final Report

- 30 November 2009 Draft Final Report
- 17 January 2010 Final Report (ESA) and (LTU)

Phase G: Post Final Report Submission

- Mid January 2010 Final Presentation at LTU
- Mid February 2010 Scientific Paper final draft
- Continue outreach activities and webpage updates

The taskings of the team for the post-flight data analysis were set prior to the MTR. The reel.SMRT system was anticipated to provide a wealth of sensor data including images and videos, acceleration data in both the MAIN Payload and FISH, housekeeping data, temperature data and much other information with coupled effects on the system. Each subsystem was to be responsible for processing their own feedback data relevant to their requirements. Two team members together were to be responsible for writing the data fusion and processing algorithms required to determine the performance of the FISH with respect to acceleration in the x, y, and z dimensions. This analysis was developed such that it could have been used during launch week to obtain preliminary performance values immediately following the flight.

However, as no acceleration data was recorded for the drop achieved, except on the internal FISH SD card, the only acceleration data to be processed is that for the FISH before the drop. Temperature sensor data was recorded for various locations within the MAIN Payload as well as the temperature sensor within the FISH. This data is shown in Chapter 8.

5.3.3 Ordering of Components

Ordering of some key components commenced immediately following the PDR and continued into mid-July, as component selections were optimised and modified based on design iterations. However, for some components this process was delayed due to lengthy negotiations with suppliers and searching for the lowest cost option that met the required performance. At the MTR, it was believed that almost all components were received. Exceptions included some electrical small parts as well as the MAIN Payload batteries, which underwent much analysis to choose both the safest and most cost-effective option and were ordered in mid-August. The FISH accelerometers and PCB incurred delays in the



manufacture and shipping but arrived in Kiruna just following the MTR. Many components were ordered just prior to launch week by express shipping to account for testing results and requisite design iterations.

5.3.4 Facilities for Construction and Testing

A number of resources were available to the members of the team. These included but were not limited to:

- Electrical components and diagnostic equipment from IRV and TKK
- Mechanical structural materials from IRV
- Electrical laboratory and workshop at IRV
- Mechanical workshop at IRV
- Manufacturing from IRF
- Library (including past EXUS and BEXUS materials) at IRF
- Electrical workshop at TKK
- ESRANGE MAXUS tower and cathedral for drop tests

5.3.5 Sponsorship

For details regarding sponsorship, please refer to Section 1.6, which discusses funding support.

5.3.6 Supporting Organisations

In addition to the facilitators of the BEXUS program, reel.SMRT was supported in Helsinki by TKK and in Kiruna by IRV. The physical components of this support are listed above as resources. This also allows access to professionals many of who have prior experience with space quality hardware and project expertise.

Financial support from organisations and companies are detailed in Section 1.6.

5.4 Hardware/ Software Development and Production

Significant changes to hardware or software were presented in the bi-weekly team meetings prior to CDR and in the weekly updated between the CDR and the MTR. Between the MTR and launch week significant changes were dealt with in location. When the change directly affected an interface with another subsystem, both subsystems arranged to discuss the design and present their solution together. Changes were recorded in the component lists or design documentation on the DLR SharePoint site. This SED is updated with the as-built and as-flown designs.

5.4.1 Mechanical Hardware Development

The very first step in the mechanical subsystem hardware development was to purchase and obtain the reel and line to be able to finalise the design of the MAIN

and FISH, which were completely finished at the MTR. Machine drawings are now completed and the building phase has started in June. As seen in Figure 5.2, almost all the components have been purchased and received with the exception of a few minor parts.



Figure 5.2 Showcase of the Mechanical Hardware

The construction and assembly phase has started in the last week of May and throughout the first half of June. This time was planned to be sufficient for the construction of the prototype, however, due to certain issues and delays, the construction was not completed but at about 95 % complete for the FISH payload and about 85 % complete for the MAIN payload. The issues and delays encountered were related mainly to the unavailability of the labs. The remaining construction of the mechanical prototype were carried out in the last three weeks of August by Mikael Persson in Kiruna. The construction phase seems short but, as seen in Section 3.5, the use of off-the-shelf components and some modifications to the design have led to a simplification of the construction of the prototype; previous BEXUS experiments also showed that short construction periods were counter-intuitively effective. By observing the machine drawings of Appendix 5.8, one will realize that most custom made parts are very simple to machine, most often only involving rough cutting and drilling of holes and taps.

As mentioned before, most of the components were purchased and received swiftly and cheaply because local suppliers were found to meet nearly all of the needs. Some special items such as the reel and the line caused some commotion because they were obtained from off-shore sources and complications have arisen in clearing customs, with multiple cases of the components being returned to sender. However, they are now in our hands and the final design, although made



late as compared to the original planning, is now complete. A few minor items remained to be purchased. Finally, towards the end of August and start of September, all components were purchased, obtained, and assembled to the system.

As the mechanical parts were completed, the tests were performed as described in Section 4.5.1. Design iterations have occurred during this phase and were taken into account through contingency planning as part of the testing phase. The reel, the major element of the design, on which many interfaces rely, can now be tested for its behaviour in low-pressure environments, cold environments, and for resistances to humidity in addition to cold temperatures. Several structural tests can be performed as mechanisms are assembled many of which are still missing a few parts to be fully assembled and ready for testing. It was foreseen that all the hardware will be purchased and acquired by the end of June which has more or less been achieved except for some leverage and ordering delays. In summary, Figure 5.3 shows graphically the progress in the construction of the MAIN payload in mid-july. Some selected pictures follow to showcase the progress of the hardware's construction throughout the summer.

Since the middle of the summer, several changes occurred and several issues were encountered. From the start of august, the completion of the MAIN payload's mechanism was underway. No major machining problems were encountered and the final mechanism corresponds for most parts to the initial design found in the technical drawings section of the mechanical subsystem appendix. Certain small issues lead to extra spending such as obtaining an expensive dye tool to make the threads on the reel to motor interfacing drive-shaft, an M5 0.5mm pitch thread to be precise.

As of the machining itself, the help of the staff at the IRF workshop was very beneficial for guidance but all the actual machining was performed by Mikael Persson within the second week of June and the last three weeks of August. Materials were acquired from local suppliers in Kiruna with the exception of some which were obtained directly from IRF in their excess material inventory, including a very hard to find slab of steel to support the reel. Finally all pieces were successfully assembled and tested.

Many problems were encountered when acquiring a vast amount of off-the-shelf components. The two main problematic components were a set of space-ready sleeve bearings and a set of shaft couplers. It was difficult and frankly, the suppliers did not help at all, to get those components in time and final integration was not possible before the end of August leave some work for the responsible personnel of other subsystems, including electrical and software, to complete the final stages of mechanical hardware development.

During September, the main developments to the mechanical hardware was the final assembly with the newly arrived components (see above), the mounting of boxes to hold the electronics, the redesign of the bail release mechanism (see

section 3.5.2), and the manufacturing of a replacement part on the reel. As mentioned in the subsystem test section, a critical part of the reel showed weakness and eventually broke during full-load tests and needed to be replaced. This part was forged, literally forged, by Kjell Lundin from IRF out of steel which provide much more strength and reliability than the original plastic part.

Finally, in the last week, the launch week, the thermal regulation system was put in place via the temperature sensors and a set of *Omega* heaters. They were put on the components which required a narrower temperature range for operation. These included the safety brake, the reel, the motor controllers, the battery pack, and the micro-controller board. Temperature sensors were put adjacent to those heaters, not monitoring the temperature of the heaters of course, but of the parts the heaters were heating. With regards to thermal issues, one issues was found at the last minute when performing tests in the MAXUS tower which showed that the line on the barrel of the reel could get loose as the reel shrinks with decreasing temperature. It was apparent that the reel needed thermal regulation, but additionally, the line interface to the reel was modified such that the end of the line was rigidly attached to the barrel by looping in through holes in the barrel and tying it, this will prove to be a factor in the flight diagnostics section.

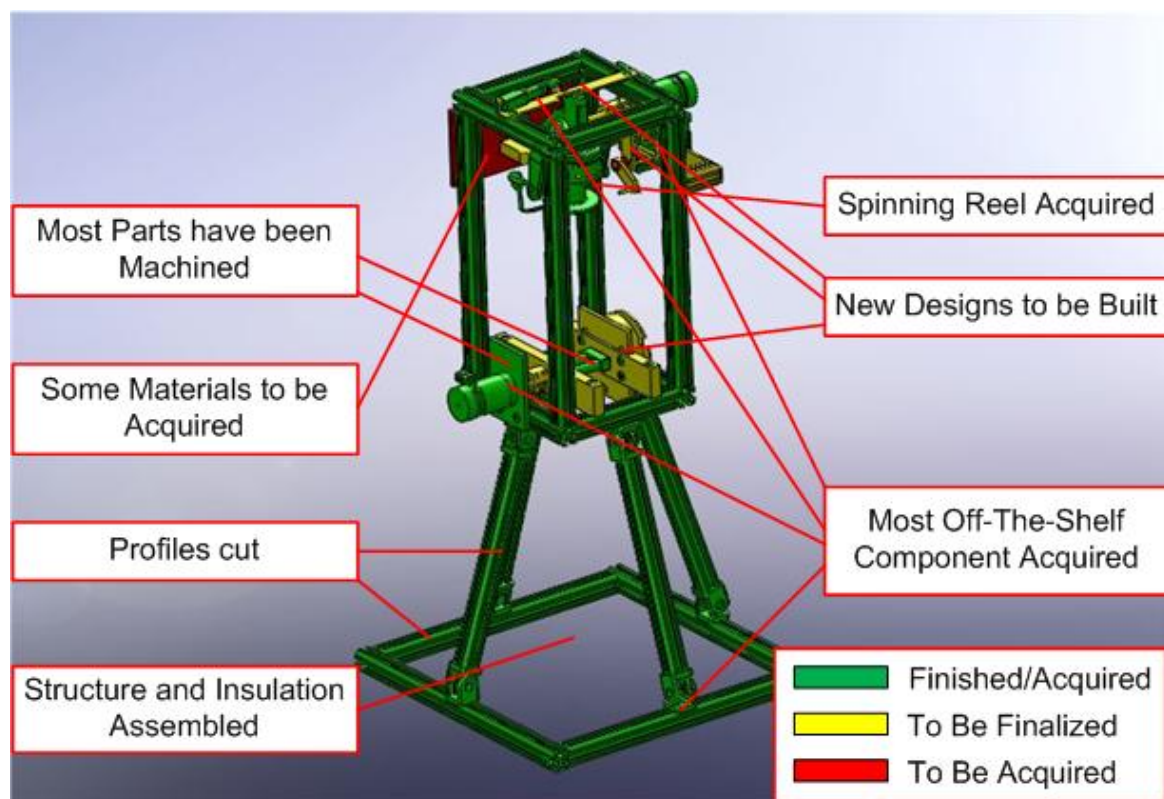


Figure 5.3 Colour-Coded View of the MAIN Payload's Construction Progress

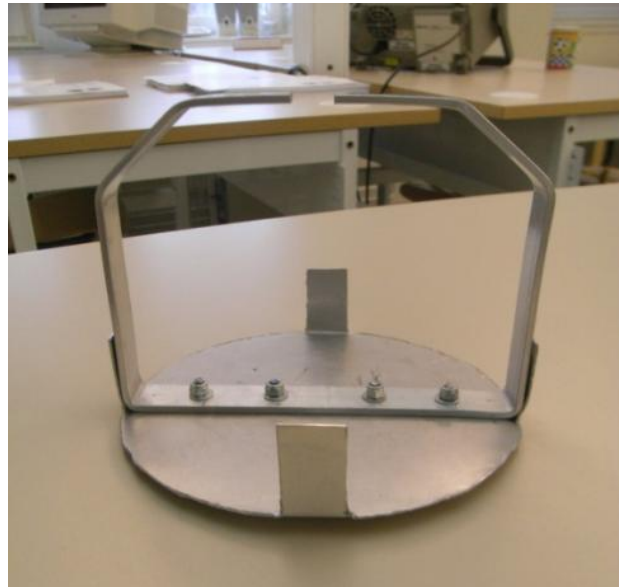


Figure 5.4 Frame of the FISH Payload



Figure 5.5 Skin and Nose Cone of the FISH Payload



Figure 5.6: The Completed FISH



Figure 5.7 Mikael and Campbell Cutting Insulation Panels



Figure 5.8 MAIN Structure and Insulation Assemblies, mid-June



Figure 5.9 MAIN Payload Enclosed in Insulation Panels, mid-June

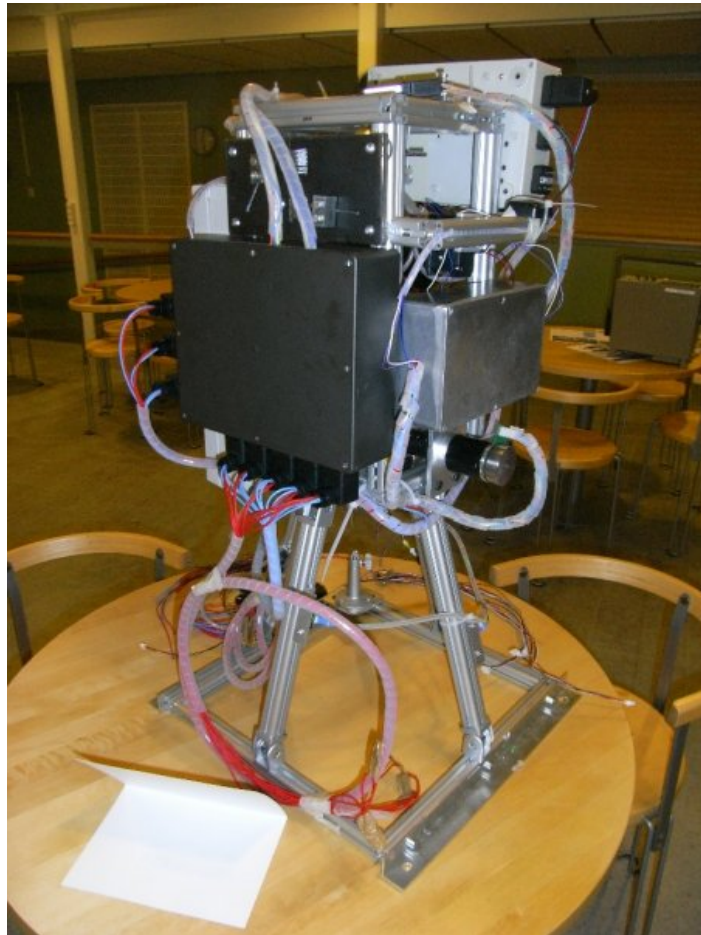


Figure 5.10 Final As Built MAIN Payload, before the Launch Campaign

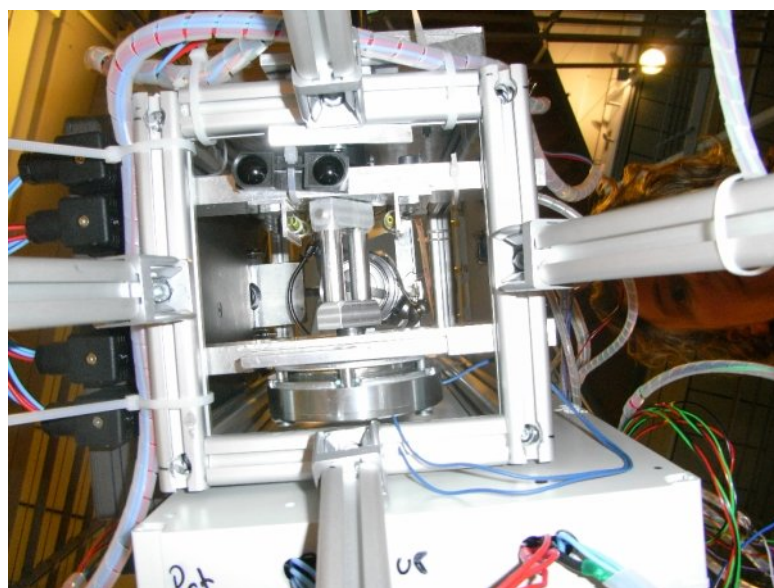


Figure 5.11 Bottom ('looking up') View of the As-Built MAIN Payload

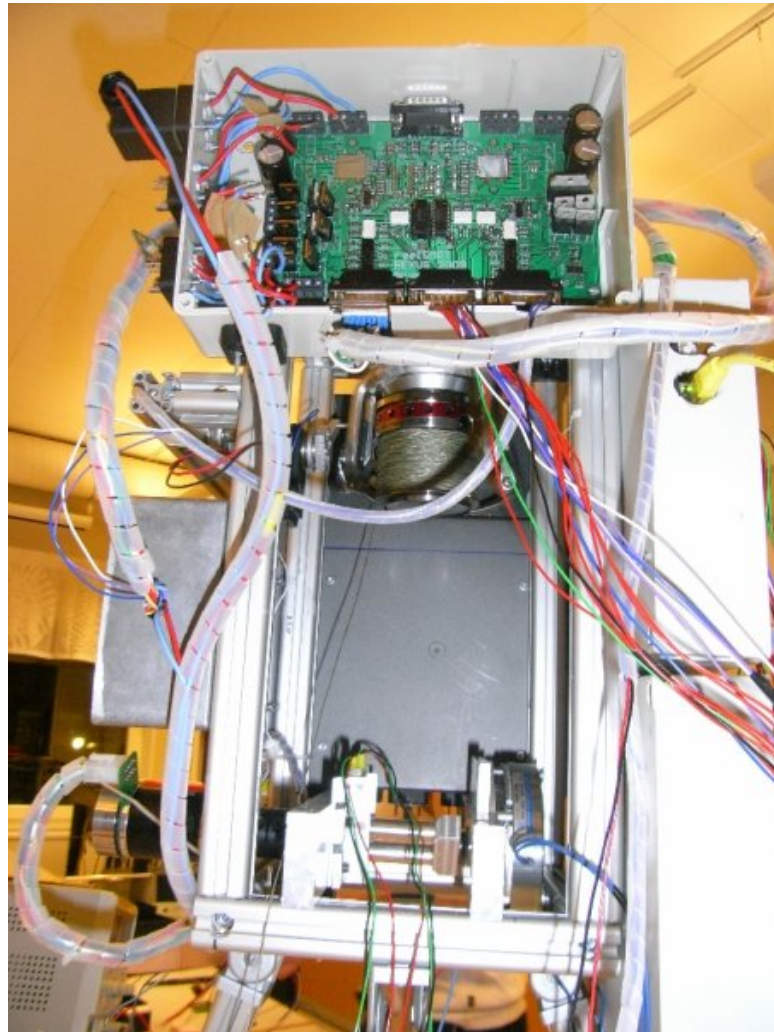


Figure 5.12 Side View of the As-Built MAIN Payload showing the Line-Guide and Reel Mechanisms



Figure 5.13 View of the As-Built Reel Mechanisms, showing the bail-release, bail-close, and motor drive

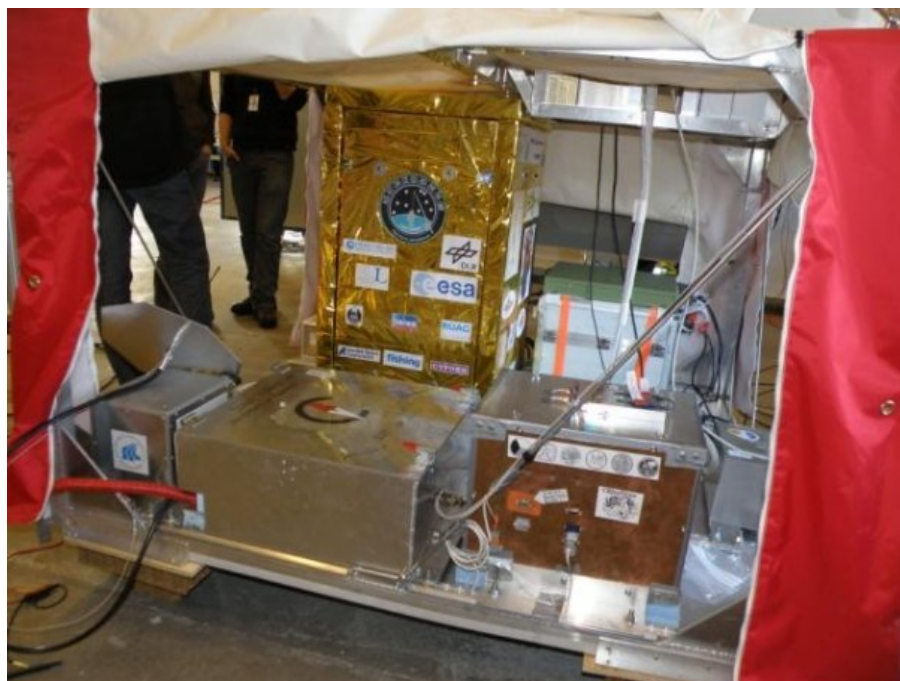


Figure 5.14 View of the As-Built reel.SMRT Experiment on the Gondola, pre-launch



Figure 5.15 IP Camera Mount in its own insulation and battery pack, mounted towards the bottom with a slight angle

5.4.2 Electrical Hardware Development

5.4.2.1 Main Payload Electronic Development

When building the electrical hardware the most important factor was to design the PCBs and start their construction. The design consisted of three PCBs in the MAIN Payload and one in the FISH. . The time taken for the PCB to be constructed was anticipated to limit the rest of the building phase. The manufacturing of the PCB was expected to take approximately one week to be made and returned to the reel.SMRT location. The PCBs were aimed be populated no later than the last week in July such that testing may begin in earnest at the beginning of August.

The PCB population occurred with one of the PCBs at TKK in Helsinki and other one in IRF because of the separation of the two electrical personnel. This was planned in order to reduce the work load for both of the electrical members.

The PCBs were made in PragoBoard in the prototyping service which offers excellent money saving. The picture of PCB is shown below.

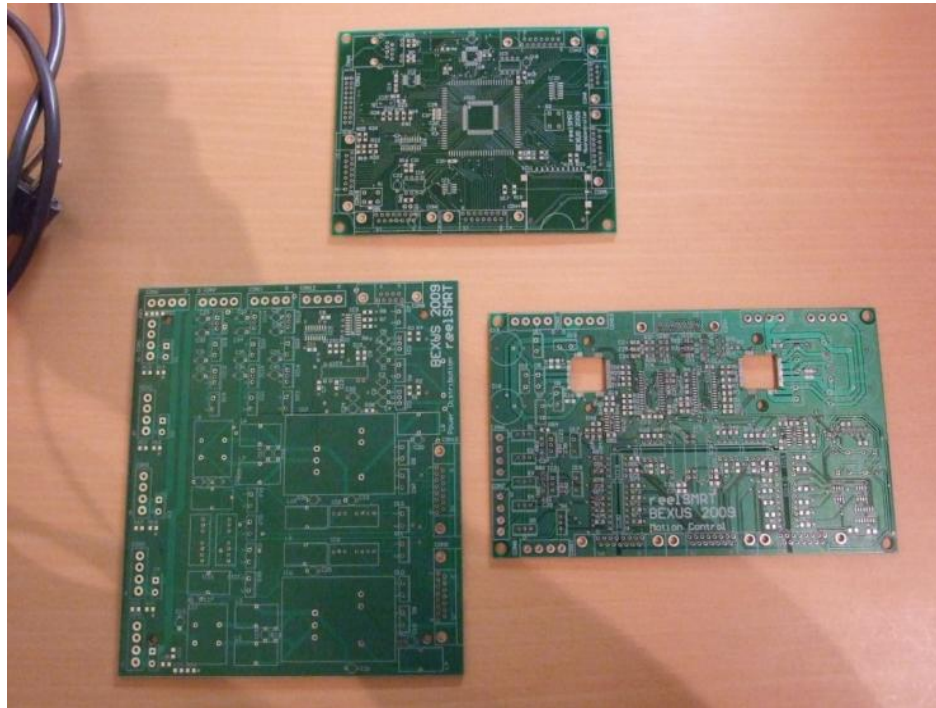


Figure 5.16 MAIN Payload PCBs

The PCBs were populated at the home of the responsible subsystem member and at the workshop of IJM Bohemia. The equipment utilised for testing during construction and diagnostics of the MAIN Payload electronics is displayed in Figure 5.16.



Figure 5.17 Test Equipment Used for Construction and Diagnostics

The pictures of all populated PCB are shown below.

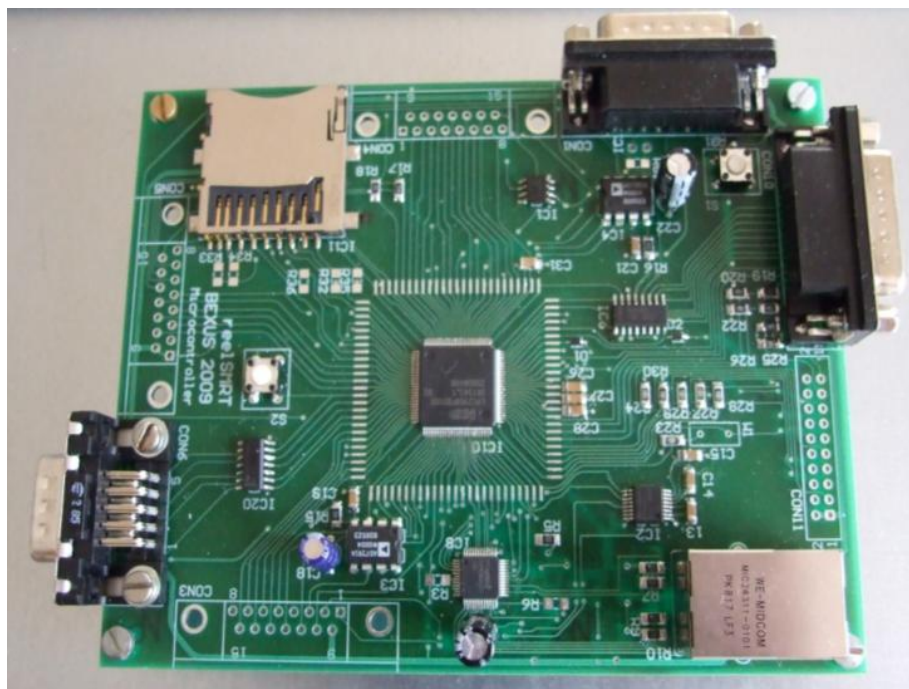


Figure 5.18 Population PCB. The Microcontroller is Visible in the Centre of the Board.

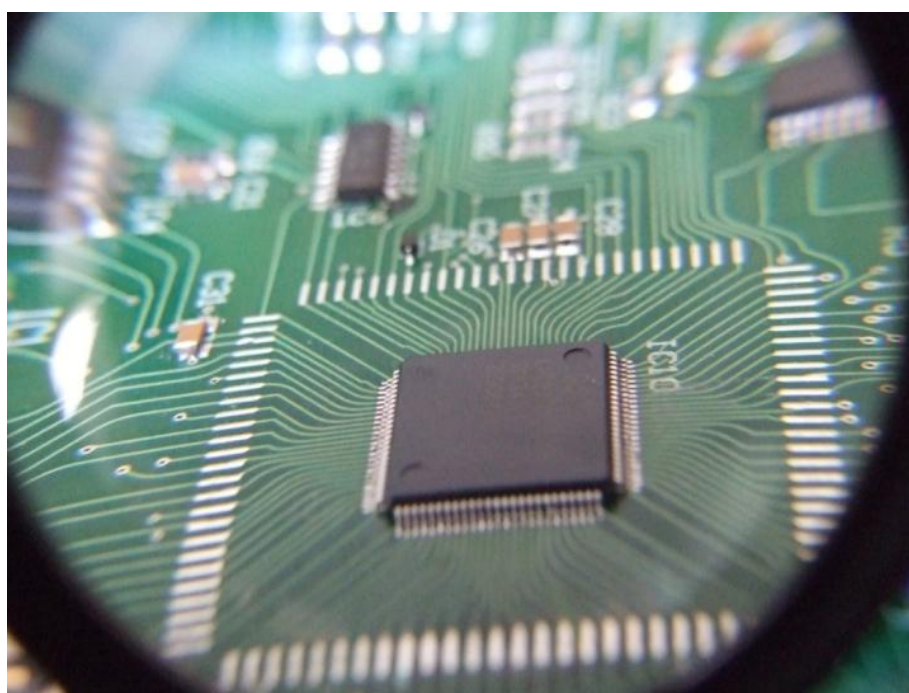


Figure 5.19 Magnified Image of the Microcontroller and the Soldering Work.

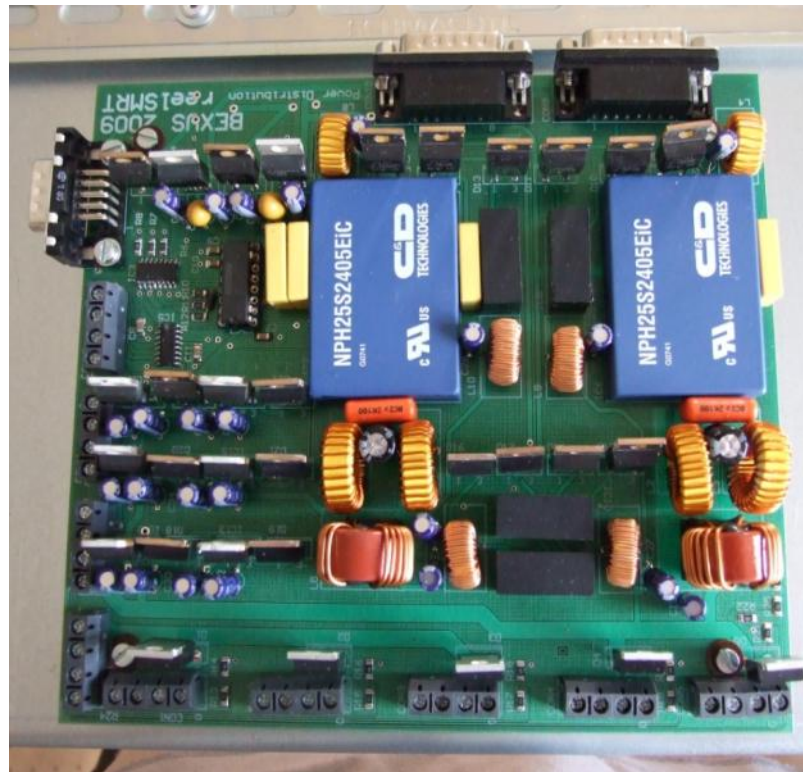


Figure 5.20 Power Control PCB

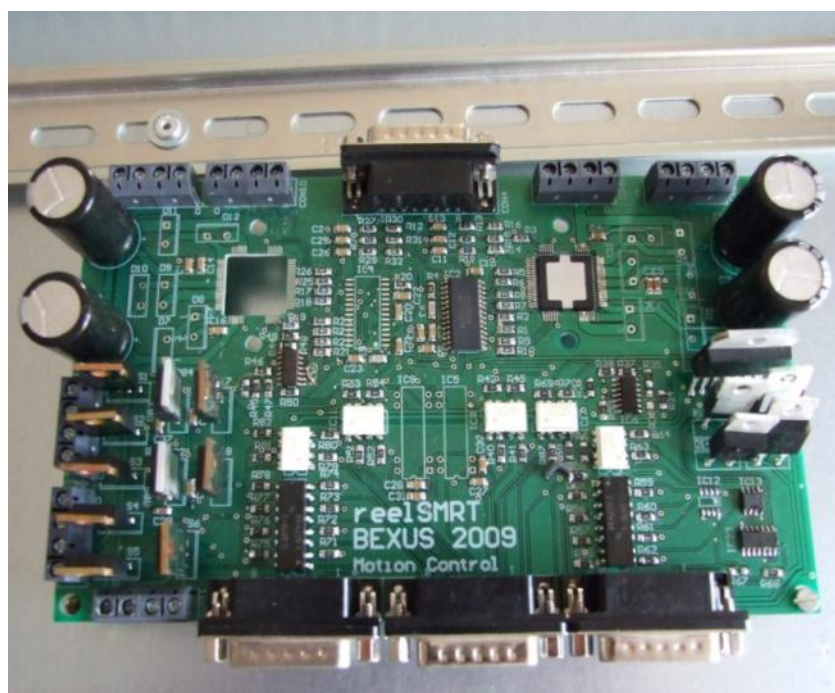


Figure 5.21 Motion Control PCB



As the test suggested, the Power Distribution PCB was not redesigned since it conformed to all hardware tests. On the other hand, the Motion Control PCB was redesigned in the week 34.

Technical Challenges

The design from the very beginning was without any prototyping. Everything was based on either previous experience or datasheets and application notes of the components used. Inevitably, several technical issues arose during the testing. There were two main parts of the design which did not work or did not work fully. The first was the microcontroller board where the interference between the Ethernet driver and the SD card resulted in not using both devices at the same time. Was the design on a 4-layer PCB, both devices could have worked simultaneously. As a result, this board was replaced by a prototyping board.

The second technical problem was caused by not putting into operation the brushless drivers implemented on the motion board. Due to rather complex circuitry, further testing was skipped and the board was partially replaced by two industrial brushless drivers.

During the assembly there were also several occasion when the joins on the surface mount components were either not conducting at all or poorly resulting in awkward behaviour of the circuitry. At one point there was also a problem when one of the SMD components was soldered wrongly.

These challenges were ultimately overcome, however could have been at least partly mitigated were a 'keep it simple' approach implemented within the Electrical Subsystem from the outset.

5.4.2.2 FISH Board Electronic Development

In Figure 5.22 the unpopulated FISH board can be seen. It was manufactured in Tallinn, Estonia by KAMITRA. This board and all of the components that were ordered are 100% ROHS compliant. Special care had to be put into not contaminating it with Lead, as this contamination would lead to the degrading of the solder, the appearance of cold soldering and would make the connections brittle, and would most likely break with the temperature changes the board would have to endure during the mission, with all of this resulting in broken connection and the malfunctioning of the board.

Some special considerations that were taken into account include:

- The use of silver based solder, without lead.



- As the melting point of the silver is different, lower than usual soldering, a lower temperature had to be used in the soldering iron, as over temperature would otherwise have over stressed the solder points.
- The soldering Iron, soldering iron mount, tip, de-soldering wick, paste and everything that came in contact with the pcb was ensured to never before have had contact with non ROHS environment, especially soldering.
- Special paste had to be used on the tip in order to keep the iron moisturized so solder would flow evenly.

The assembly and basic functionality testing of the FISH board took place in the Automation and Systems Technology laboratory of the Helsinki University of Technology and was performed by David Leal.

Challenges

The most difficult component to assembled was the three axis backup accelerometer as the packaging (quad flat no lead) was very complex to solder without professional equipment such as a heating plate. With the use of the heating plate, the accelerometer was soldered in place and then the soldering of the rest of the components took place with a fine tip soldering Iron and Multifix 425 – 01 Rework Flux for the Soldering of the Microcontroller and ADC, and NO-Clean X32 flux pen for some other components. All passive components such as resistors, capacitors and crystals were soldered without any flux besides the one contained in the solder itself. The end product of this process was the populated board shown in Fig 5.23.

During final integration and testing, there were problems with the interface to the micro controller. The initial design used one separate clock for the communication and at the same time for clocking the converter. Due to the fact that the microcontroller did not support high speed communication, the design had to be changed. Unfortunately, there was not enough time for the proper iteration of the design. This resulted in rather picante work with soldering iron and rewiring some of the connection and literally connecting SMD components with wires. This work was assisted by ESRANGE personnel during launch week. Prior to flight, this system was working as intended with acceleration data being received at the ground system over the Zigbee connection.

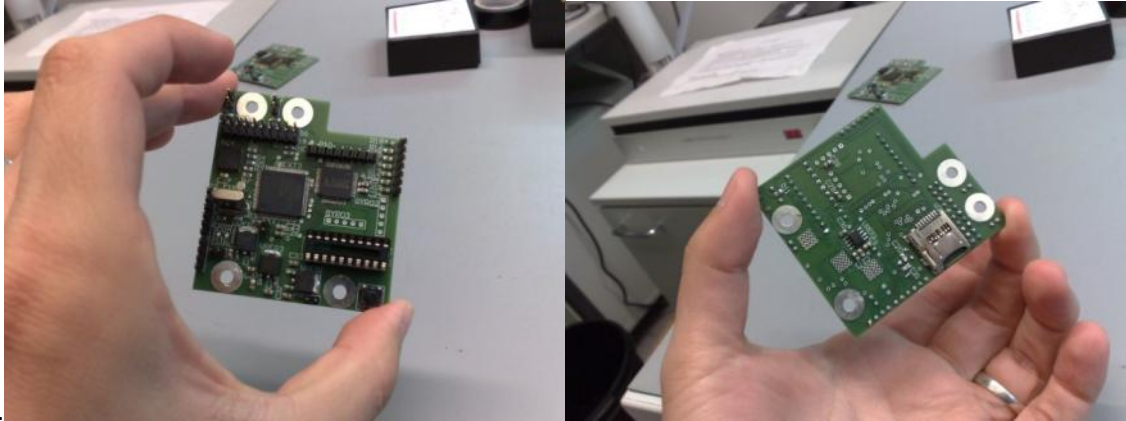


Figure 5.22 Populated FISH PCB Board upper (left) and lower (right) sides.

5.4.3 Software Development

The software for both microcontrollers was under development using the evaluation board MCB2300 from Keil. It allowed for easy testing and troubleshooting of software parts in a very early stage of the software development part. For programming, the integrated development environment (IDE) Eclipse was used. It acts as a graphical user interface of the popular gnu-gcc compiler (36). During the development of the electronics, when the sensors and actuators were not available for programming, the development of the software was still able to be carried out using the evaluation board.

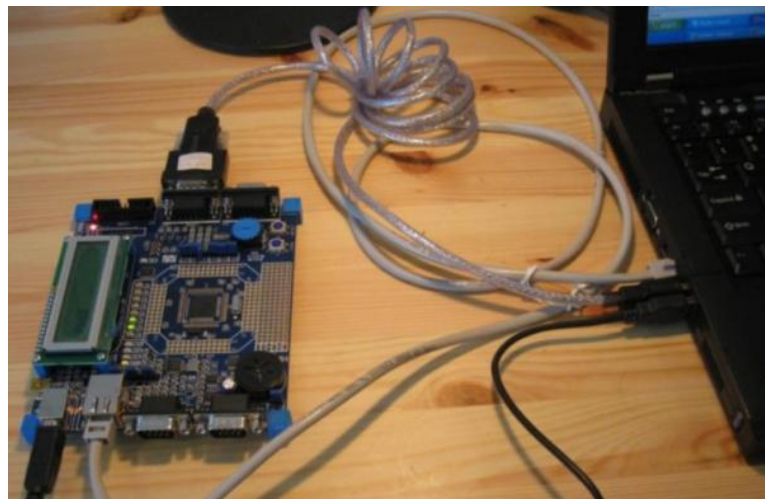


Figure 5.23 The Evaluation Board Test Set-up

In addition to the Eclipse IDE and the gnu-gcc compiler, the real-time operating system FreeRTOS (37) was used. Most of the peripherals of the microcontroller were supported by FreeRTOS. For the Ethernet stack, however, the free software suite μ P was used (38). All programming was performed on Microsoft Windows

based computers. The microcontroller was be programmed using the ISP interface and/or the JTAG connector. For testing of the software the unit testing procedure was be used. Additionally, each control algorithm was tested according to the test graph in Section 4.5.3.

The test platform via a FreeRTOS simulator was designed and utilised. This method controlled the way of implementation. The development environment was been setup with Eclipse and evaluation board was tested with the FreeRTOS demo project. The communication protocol was been designed and network ability of microcontroller tested prior to the MTR.

Prior to the MTR, the complete program structure on the microcontroller was implemented and tested with the communication protocol in two evaluation boards. A LAN cable was used for the E-link simulation and a cross serial cable was used for xBee simulation (Figure 5.24). One evaluation board performed as the FISH and generated test data to simulate the operation. Another board performed as the reel.SMRT payload and propagated the data to the ground station. Both evaluation boards performed well in both normal data propagation and command response. Ground station network module also has been implemented to test the communication protocol.

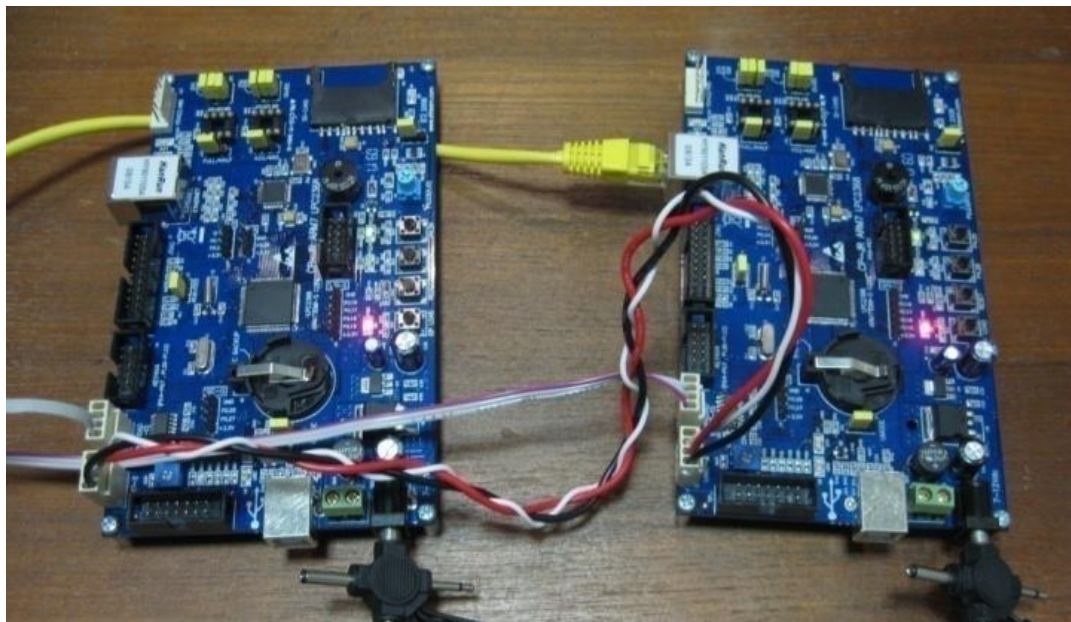


Figure 5.24 Communication Protocol Test Setup.

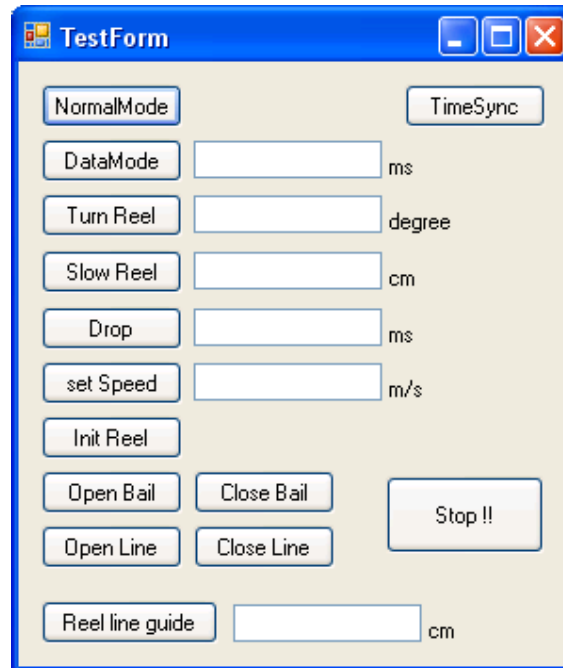


Figure 5.25 Ground Station for Communication Protocol Testing.

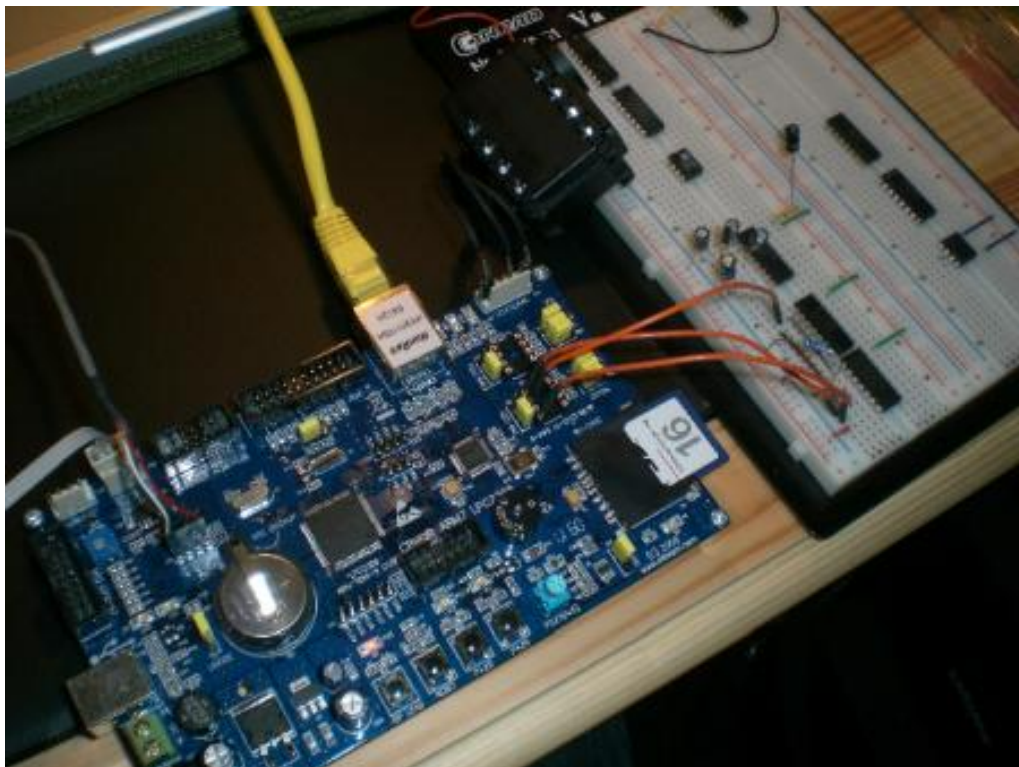


Figure 5.26: Evaluation Board with Connected Electronic Components



5.5 Risk Management

The risk management methodology involved each subsystem filling out a risk matrix to identify the critical risks, and updating these risks at each design review. These risks were further divided into implementation risks and mission risks.

This involved establishment of potential failure scenarios and their severity and probability for each mode of the mission. A value of 5 represented the greatest severity and highest probability for each case. Any risk involving safety to personnel incurred a severity value of 4 or 5. The critical risks were identified from this matrix, and are presented in this chapter. For each critical risk, an ID number, name, description, severity and probability and total risk and actions taken to minimise the probability and severity of the scenario were described. The reaction to this risk and the recovery method were also displayed. The complete in-depth risk analysis is shown in the Appendices of individual subsystems.

5.5.1 Mechanical Subsystem Risk Management

5.5.1.1 Mechanical Implementation Risks

For the implementation phase of the mechanical design, the following major risks have been identified:

ID	I – M 03
Name	Destruction of mechanical parts
Description	Parts are destroyed during implementation or testing of the experiment.
Consequences	Objectives cannot be achieved
Severity	2
Probability	1
Total Risk	2
Prevention	Have spare parts and excess material
Reaction	Replace faulty parts or machine replacement parts from spare material
Recovery	Full recovery after test

21 Risk ID I-M03.



5.5.1.2 Mechanical Mission Risks

During the operation of the mission the following major risks have been assessed.

ID	M – M 01
Name	Loss of Reel Drive Motor during the Brake Phase
Description	When the FISH is being decelerated the reel drive motor is used to flip the bail to catch the line and transfer the force through the bail and the brake, possibly transferring strong torques through the drive
Consequences	The FISH will continuously fall until the line runs out
Severity	3
Probability	1
Total Risk	3
Prevention	Testing of the system at the mission temperatures will be conducted before launch
Reaction	Use of a backup lock mechanism to stop the line (line guide)
Recovery	Line guide will be used to reel the FISH back up and the FISH will be housed safely in the SMRT payload

22 Risk ID M-M04.

ID	M – M 05
Name	Loss of Line Guide Drive during all phases
Description	If the brake fails then the line guide will be used. The line guide will turn and stop the line and reel it back up
Consequences	The FISH will continuously fall until the line runs out
Severity	2
Probability	1
Total Risk	2
Prevention	Testing the line guide to make sure it works
Reaction	The last winding of the line will be glued to the barrel of the reel which will rip off and slow the FISH to a stop
Recovery	The FISH will be reeled back by the reel, or left hanging if the reel drive is also broken and then collected with the balloon

23 Risk ID M-M05.

ID	M – M 06
Name	Failure of Line Guide during all phases
Description	If the line guide is being used then another part has already failed. The line guide will use direct friction with the line to stop it and then reel it back up
Consequences	The FISH will continuously fall until the line runs out
Severity	3
Probability	1
Total Risk	3
Prevention	Testing the line guide operation.
Reaction	A guard below the line guide to catch the guide if it falls. Let the FISH hang in the position that it has fallen to from the balloon
Recovery	The mission is over and the FISH will be collected with the balloon

24 Risk ID M-M06.

ID	M – M 08
Name	Failure of Line or Interfaces of line during Braking Phase
Description	The line or line interfaces could break or come undone during any phase of the mission
Consequences	The FISH will fall to the ground at terminal velocity
Severity	4
Probability	1
Total Risk	4
Prevention	Test the strength of this line at the mission temperature
Reaction	The parachute will be deployed and the FISH velocity will be reduced to a safe speed
Recovery	The FISH will be retrieved if possible, otherwise will remain where it lands.



25 Risk ID M-M08.

ID	M – M 09
Name	Failure of Line or Interfaces of line during the Line Guide use
Description	The line guide is to be used if the reel fails. The friction of this line guide against the reel might cause it to break
Consequences	The FISH will fall to the ground at terminal velocity
Severity	4
Probability	1
Total Risk	4
Prevention	The line frictions will be tested at the correct temperature
Reaction	The parachute will be deployed and the FISH velocity will be reduced to a safe speed
Recovery	The FISH will be retrieved if possible, otherwise will remain where it lands.

26 Risk ID M-M09.

Thus the areas that have a high severity rating if failure occurs, are the break, line, line guide and catch mechanism. The chance of these mechanisms failing was deemed to be relatively low and many precautionary actions were implemented to stop a complete failure. The majority of high severity situations were reduced via implementation of the line guide which was able to lock of the line if an irregular falling occurs. This line guide would have stopped all situations of failure that may have occurred above the line guide, if the line was at its intended length of 200 m. However, since the line was limited to 70 m length to reduce forces on the structure should the bail not be able to close, the line guide did not have enough time to react to the bail not closing properly during the flight.

The only major risk that was not mentioned was the potential for the line or interfaces to break and hence cause the FISH to fall to the ground. To reduce the potential of this happening was by implementing the strongest fishing line that is on the market, which is able lift an approximately 90 kgs. Also a parachute has been placed inside the FISH to ensure if all else fails then capsule will slowly descend. Thus for all possible mechanical failures the probability for a safety risk to occur is highly improbable. However, this was the risk that eventuated as critical during the flight. The diagnostics for this is discussed in Section 8.9.



5.5.2 Electrical Subsystem Risk Management

5.5.2.1 Electrical Implementation Risks FISH

For the implementation phase of the electronics, the following risks were identified:

ID	I - E03
Name	Destruction of PCB
Description	PCB is destroyed or heavily damaged
Consequences	Repairs or new PCB needed
Severity	3
Probability	3
Total Risk	9
Prevention	
Reaction	Try to repair the PCB board or order a new one
Recovery	Recovery is possible

27 Risk ID I-E03.

5.5.2.2 Electrical In-Flight Risks MAIN Payload

For the mission phase, the following risks were identified about the FISH payload in the Electrical Subsystem:

ID	M - E01 (I - Implementation, M – Mission))
Name	Destruction of a critical component
Description	Critical component (microcontroller, AD converter, analogue circuitry, voltage reference, precise accelerometer, wiring between PCB's and PCB's itself) stops working during the mission.
Consequences	Objectives cannot be achieved
Severity	5
Probability	3
Total Risk	15
Prevention	Using high quality components, proper testing
Reaction	Notifying ground station
Recovery	Recovery not possible

28 Risk ID M-E01.



ID	M - E03
Name	Malfunction of ONE battery set
Description	One battery pack stops working, gets shorted
Consequences	Limited operational time or/and deterioration in quality of the acquired data
Severity	3
Probability	3
Total Risk	9
Prevention	Implementing active (current monitors) and passive (fuses) protection circuits, vigorous testing of power supply
Reaction	Notifying ground station, using power safe down mode
Recovery	Fully recovery not possible

29 Risk ID M-E03.

ID	M - E08
Name	Malfunction of memory
Description	Memory cannot be used for storing data.
Consequences	Previous data may be lost if not successfully sent to the MAIN Payload.
Severity	4
Probability	1
Total Risk	4
Prevention	Using high quality components, proper testing,
Reaction	Monitor Data flow into MAIN Payload, use microprocessor internal memory, restart memory??
Recovery	Recovery may be possible during the mission

30 Risk ID M-E08.

ID	M - E09
Name	Malfunction of memory and communication link
Description	Memory cannot be used for storing data, communication link stops working.
Consequences	Previous data may be lost if not successfully sent to the MAIN Payload. Data only for circa 3 drops could be stored in the main microcontroller memory.
Severity	5
Probability	1
Total Risk	5
Prevention	
Reaction	Using data compression procedures to prolong data storage, depending when the failure occurs, keep only certain data, discard the rest, try restarting memory
Recovery	Recovery is not possible during the mission

31 Risk ID M-E09.

5.5.2.3 Electrical In-Flight Risks

For the mission phase, the following risks were identified about the MAIN Payload in the Electrical Subsystem:

ID	M - E11
Name	Malfunction of power electronic of reeling motor
Description	The H-bridge itself or logic circuitry of power electronic of reeling motor stop working
Consequences	The experiment has to be stopped
Severity	4
Probability	2
Total Risk	8
Prevention	Using components for power electronic exceeding the maximal current by the factor of 2
Reaction	Activation of emergency reeling system
Recovery	Recovery is not possible during the mission

32 Risk ID M-E11.



ID	M - E12
Name	Battery becoming critically discharged such that it could explode
Description	Without a PCM the MAIN Payload battery have a low risk of being critically discharged.
Consequences	End of experiment, potential injury to personnel collecting the experiment if they are in close proximity
Severity	5
Probability	2
Total Risk	10
Prevention	Development of a battery safety plan to be delivered to ESRANGE in mid-September. Also monitoring the batteries from the ground station and shutting down the experiment if batteries are too low. Batteries have much more power than required and so this scenario is not expected to occur.
Reaction	Isolate explosion, only allow expert personnel to approach and contain. Perform a review/investigation of why the situation occurred.
Recovery	Recovery is not possible during the mission

The main areas that were assessed as a high potential risk were the PCB and the Batteries. If the PCB was broken during the implementation and construction of the circuit board then it would take a month for another one to come in hence delaying the project by this amount. This risk was mitigated by making sure that the PCB was safe at all times and no dangerous activities were conducted near it. For safely risks there was a potential that the batteries will self destroy if they are deeply discharged or overcharged numerous times. The stop this from occurring the PCM has been implemented. For an operational failure there is a potential that the batteries will fail. This system was been made redundant via the use of batteries connected in parallel with every battery having a fuse (poly switch).



5.5.3 Software Subsystem Risk Management

5.5.3.1 Software In-Flight Risks

For the mission phase, the following risks were identified about the FISH payload in the Software Subsystem:

ID	M - S 01
Name	Total Software crash
Description	Program in one (or both) microcontroller fails
Consequences	If FISH controller fails: - No scientific sensor data - Not possible to prove microgravity -> mission failed - Reeling process not affected -> no increased risk for people on the ground If payload controller fails: - No data at all - Reeling not possible - If in free-fall mode: Loss of FISH (Dangerous!)
Severity	5
Probability	1
Total Risk	5
Prevention	"Watchdog" checks microcontroller for software crashes and resets it if necessary. A well defined "Power-on-reset" sequence brings the system into a defined safe state (see software design)
Reaction	Implementation of "watchdog" and "power-on-reset"
Recovery	Full recovery



ID	M - S 02
Name	Loss of electrical power
Description	One (or both) microcontroller(s) fail to operate
Consequences	If FISH controller fails: - No scientific sensor data - Not possible to prove microgravity -> mission failed - Reeling process not affected -> no increased risk for people on the ground If payload controller fails: - No data at all - Reeling not possible - If in free-fall mode: Loss of FISH (Dangerous!)
Severity	4
Probability	2
Total Risk	8
Prevention	Cannot be prevented from software site. But for low power situations "Brown-out" detection is implemented. This avoids unexpected behaviour of the microcontroller if supply voltage drops below design limit.
Reaction	Brown-out detection with controlled shutdown
Recovery	Not possible to recover

ID	I - S 01
Name	Wrong program version flashed to microcontroller
Description	The controller contains an outdated version of the operating software and was not updated before the launch
Consequences	Unwanted behaviour of experiment. Possible loss of parts of the sensor data or even complete failure of mission
Severity	4
Probability	1
Total Risk	4
Prevention	Typical human error. Has to be avoided at all costs
Reaction	Detailed "before launch checklist"
Recovery	Full recovery if checklist is used

ID	M - S 03
Name	Loss of communication FISH - payload
Description	xBee Pro connection fails
Consequences	- Scientific sensor data from FISH cannot be transferred to payload (and ground station). - Sensor data is stored in FISH instead
Severity	4
Probability	2
Total Risk	8
Prevention	Use of a simple transfer protocol
Reaction	Implementation of memory in FISH for sensor data storage
Recovery	Fully recovered

ID	M - S 04
Name	Loss of communication payload - ground station
Description	E-Link connection fails
Consequences	- scientific sensor data cannot be transferred to ground during flight - status information is not available on ground during flight - experiment procedure cannot be altered from ground
Severity	3
Probability	3
Total Risk	9
Prevention	It is not allowed to use an automatic test sequence in case the communication link is disturbed. Therefore, a loss of communication between payload and ground station will mean the end of any further drop or reel tests
Reaction	Use of a highly reliably communication link (E-Link)
Recovery	Fully recovered



ID	M - S 05
Name	Payload: Loss of reel speed sensor information
Description	The speed of the reel cannot be detected any more (nil or faulty data)
Consequences	Experiment cannot be carried out: Contingency mode (see software design)
Severity	5
Probability	2
Total Risk	10
Prevention	Not possible to be prevented by software (see Electrical)
Reaction	Implementation of proximity sensors that measure the distance between FISH and MAIN Payload when the FISH is approaching the MAIN Payload. It is then possible to slow down the reel motor to avoid damage to the structure.
Recovery	Partially recovered (reduced performance)

ID	M - S 06
Name	Payload: Loss of bail position sensor information
Description	The position of the bail (open/closed) cannot be detected (nil or faulty data)
Consequences	Not possible to detect if in freefall mode or slow reel mode
Severity	3
Probability	2
Total Risk	6
Prevention	Not possible to be prevented by software (see Electrical)
Reaction	Implementation of a backup bail position detector procedure which detects the movement of the FISH from accelerometer data. If bail is open: acceleration, If bail closed and reel motor stopped: no movement or deceleration
Recovery	Partially recovered (reduced performance)



ID	M - S 07
Name	Payload: Loss of reel motor position sensor
Description	The movement of the reel motor cannot be detected any more
Consequences	Slow reel experiment and reel up cannot be controlled
Severity	3
Probability	2
Total Risk	6
Prevention	Not possible to be prevented by software (see Electrical)
Reaction	Usage of accelerometer information (on the FISH) to derive reel motor movement
Recovery	Partially recovered (reduced performance)

ID	M - S 08
Name	FISH: Loss of accelerometer and/or gyro sensor information
Description	One or more values of the inertial sensor platform are not valid
Consequences	Primary objective of experiment cannot be reached (measurement of microgravity)
Severity	5
Probability	2
Total Risk	10
Prevention	Not possible to be prevented by software (see Electrical)
Reaction	If only one axis fails, it should still be possible to extract a reduced set of data for post processing
Recovery	Partially recovered (reduced performance)

In summary, the most severe risk from the software subsystem point of view was a permanent power loss of one of the two microprocessors. In order to avoid this from happening, the power supply to both microcontrollers was designed to be dual redundant. Even in the rare event that both power supplies failed to operate the microcontroller would have shut down in a pre-defined manner.



6 OUTREACH PROGRAMME

reel.SMRT has had a heavy focus on presenting the work during and after completion of the BEXUS high altitude launch to promote awareness and interest in the project and the REXUSBEXUS Program.

6.1 Presentations

Two presentations have been conducted at schools in Australia (39) (40); both were well received and had large audiences.

Further presentations have been carried out at the university campus IRV (41) as part of the coursework for some of the students involved. These followed the PDR and CDR presentations for BEXUS; these were attended by both staff and students voluntarily.

A presentation was made during the summer session of the International Space University's Space Studies Program (42) at the NASA Ames Research Centre in California, USA.

The team is both hindered and blessed by the dispersion of the SpaceMaster students (42) involved. Already, three of the team members are or have been based in Japan, Finland, and Germany with the remaining six in Kiruna for most of this period. The four of the six who remained in Kiruna moved to universities in England (Cranfield University) and Finland (Helsinki University of Technology). Members of the team has met with, recommended the programme and/or advised BEXUS 10/11 applicants from both the International Space University and Cranfield University

Currently, reel.SMRT plans to attend the ESA PAC Symposium for balloons and sounding rockets, Acta Astronautica, the American Institute of Aeronautics and Astronautics conference and the International Astronautical Federation's International Astronautical Congress. The team is also investigating microgravity research symposiums to increase awareness of the possibilities made available by the reel.SMRT system.

6.2 Outreach Payload

0.5 kg of the mass budget were allocated to Outreach. reel.SMRT utilized this volume for outreach activities by sending letters, certificates, stickers and patches to the Stratosphere for fundraising, recognition of supporters and outreach post-flight.

6.3 Outreach Competition

250 grams of the 0.5 kg allocated to Outreach was dedicated to a competition that was held over the months of June, July, August and September. This competition was open to students worldwide of a primary and secondary level. This was

advertised through the reel.SMRT web page and the sponsors of the project to ensure a wide coverage.

Young students (5-18 years old) from around the world were invited to submit designs that can be printed onto a sticker and stuck onto the FISH by the team. The winning entries were selected by a committee comprised of Mark Fittock, Katherine Bennell and Campbell Pegg.

Over the four categories (ages of 4-6, 7-10, 11-13, 14-18) there were a total of 8 entries. A winner was chosen from each category excepting 11-13 due to the lack of entries in this category.

Due to the number of entrants, it was possible to fly all students' entries on the main payload and the winners of each category. All entrants received a reel.SMRT patch flown on-board the payload as well as a certificate, mission patch stickers, their flown drawings stuck on the gold foil, pictures of their drawings on the balloon and gifts from ESA. The winners were rewarded with the opportunity to fly an object of their choice (must be suitable for flight) up to a weight of 200 g. Only one of the three winners took advantage of this opportunity and chose to fly a football card. Further detailed terms and conditions can be found in Appendix 6.4.

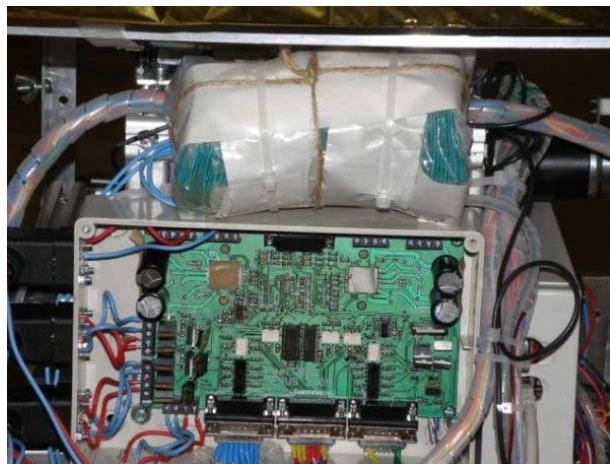


Figure 6.1 Image of the mission patches and football card on the reel.SMRT system as it was flown.

6.4 Publications and Media

reel.SMRT contacted a small number of publications (see Appendix 6.5) spread from technical to local interest with scientific and personal press releases (see Appendix 6.6) concerning the current status. reel.SMRT has also uploaded a number of the press releases onto the "PRLog" webpage (43) and has now recorded 2200 (19:20 on the 04/12/2009) hits on the six press releases uploaded in different languages.



Already under negotiation is an article in “Fishing Australia”(44) and the possibility of an appearance on the Australian television show “Two Dan’s Fishing”, which is aired in Australia and the USA.

Articles about reel.SMRT will be published in Austria’s “Niederösterreichische Nachrichten (NÖN)” (45) focusing on Juxi Leitner, have been published in “Thailand’s National Newspaper” focusing on Nawarat Termtanasombat and Katherine Bennell and Campbell Pegg have been contacted by “Peninsula Living” (46) for an article. An interview with ex-team member Mark Fittock was conducted with the national radio station Triple J (47) in which reel.SMRT was discussed briefly.

Upon the completion of the flight, reel.SMRT intends to publish a number of articles with the intent of outreach. A number of popular scientific and technical periodicals have been noted for future article submission.

6.5 Webpage

The webpage is the main point for spreading information about the reel.SMRT project. The page is continuously updated with new information about the problem as well as press releases and pictures.

6.5.1 Webpage Design

The reel.SMRT webpage (48) was designed to be user-friendly and easy to use, it follows the current practices in webpage design, using XHTML, CSS and PHP, to ensure good usability. The webpage is kept in the colours of the project to generate a common identity for all publications and outreach programmes. It has undergone considerable changes since the PDR phase and continued to be developed as the project progressed. A screenshot of the home page is shown in Figure 6.2.

Its content is split into an area for the general public, one for the press and media and one especially for the BEXUS coordinators with the full SED. This is important for all interested parties to be able to easily access information that interests them.

The winners of the FISHy Design Competition were shown on this webpage, along with their winning drawings. The competition was also advertised here.

A picture gallery exists to increase the user experience and improve the visual component of the webpage. Interested media parties and sponsors were encouraged to follow this webpage and picture gallery for information.

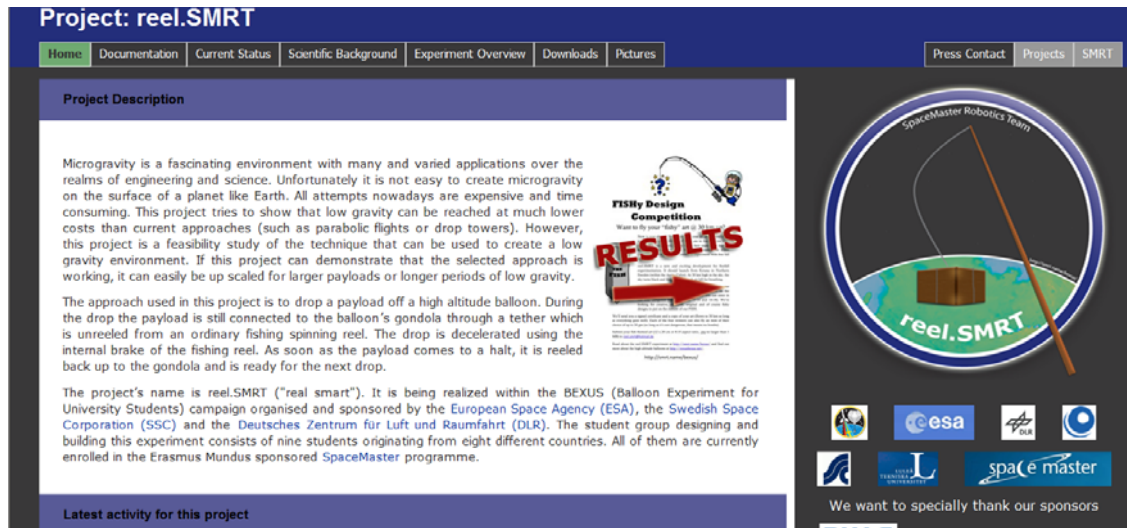


Figure 6.2 Screenshot of reel.SMRT webpage

6.5.2 Webpage Statistics

The webpage hosts all SpaceMaster Robotics Team projects. The following is a short overview of how many visitors are checking the webpage per month.

The webpage registered a spike in visitors in March, which is most probably because of the PDR workshop at that time. The number of visitors is though around 200 per month in the last few months. The visitors on the webpage come from almost all European countries, with a big number of requests also coming from the USA, this is quite normal since the USA has the biggest amount of IP addresses assigned and rented to other providers and countries. There are also visitors from Japan, Australia, (both ranking in the top 12 countries) Turkey and Canada, with all having at least 30 visitors. Figure 126 demonstrates the number of page visits each month to the reel.SMRT project page itself, and as a proportion of the SMRT parent webpage.

To clarify the terms: a hit is a single access of a file on the web server, whereas a visitor is represented by multiple hits originating from the same IP address within a given time interval.

The webpage is co-hosted, the hit count for the web server (including the Juxi.net domain) is between 10000 and 50000 hits per month with an average of around 600 (unique) visitors per month on the whole web server.

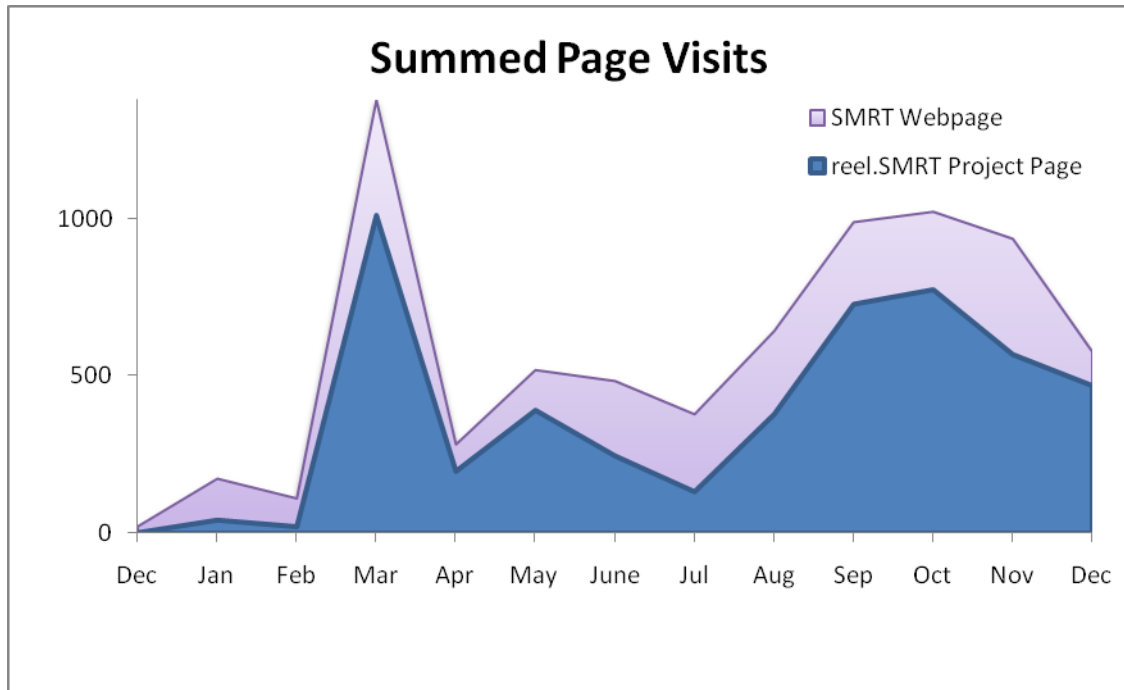


Figure 6.3 Summed page visits to the reel.SMRT Project Page and the SMRT webpage in 2009

6.6 Launch Week

For launch week, a brochure was printed that introduced the reader to the subsystem and its operation. It also advertises reel.SMRT sponsors and explains what the REXUSBEXUS programme is. Many of these brochures were printed in glossy colour and kept on the end of the workbench for anyone that may have been interested. Brochures were taken by other team members in addition to visiting supporters. These brochures have been left at LTU to be placed in the display case of reel.SMRT, so that people viewing the project can understand better what it is about. They were also distributed to sponsors and FISHy design competition winners. These brochures will additionally be of use in future conferences and outreach activities. A copy of this brochure may be found in the Appendix.

Mission patches and mission patch stickers were also made, and used as gifts for the teams supporters and sponsors. These patches were also FISHy design competition prizes and used on team soft shell jackets, in addition to being novel mementos for the team members and BEXUS-9 personnel.

The videos taken from the IP camera have been cut into user friendly clips and placed on *Youtube* for public viewing. They have been tagged with 'BEXUS' so that those searching for the programme will find these videos in their search results.

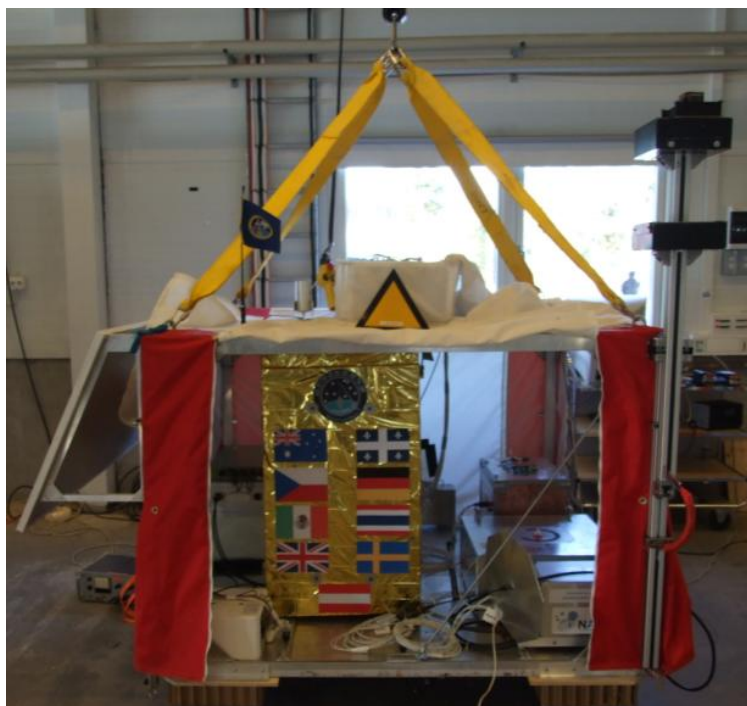


Figure 6.4 The reel.SMRT system on-board the BEXUS-9 gondola, standing out with the side panels used for outreach purposes.



Figure 6.5 The Sponsors panel and the FISHy Design Competition winners and runners-up drawing on-board the gondola.

7 INTERFERENCE

7.1 reel.SMRT – Balloon System Interference

7.1.1 reel.SMRT Forces

The forces that were anticipated to be induced from the MAIN Payload to the gondola included mainly the reaction forces to support the weight of the MAIN Payload during high perturbation phases of the flight. As stated by ESRANGE, it is expected that the gondola will experience up to 10 G in the vertical direction as well as 5 G in the horizontal directions. This would inevitably induce forces at the mounting interface between the MAIN payload and the gondola. The overall mass can be estimated at 20 kg in total, but it was prudent to include the possibility of 25 kg to have a safety margin. The payload was 85 cm in height, above the base rails of the gondola, and the centre of mass was estimated at 50 cm above the rails. This amounts to a downward force on the gondola of 250 N in steady conditions but up to 2500 N under high acceleration in the upward direction. The FISH was expected to experience a force of 5 G's when the brake was implemented to slow the FISH down. This equates to a force of 100N downwards. In the worst case example this force would then be added to the overall force to the interface to the Gondola of 350N for a steady conditions and 2600 N for high accelerations.

In addition, horizontal acceleration perturbations on the gondola could induce up to 1250 N sideways accompanied by a moment reaction perpendicular to the perturbation of 625 Nm. This moment would be reacted to at four mounting points on four corners of the 40 cm by 40 cm foot-print of reel.SMRT payload. This amounts to worst-case vertical loads, when the perturbation direction is exactly on the diagonal of the payload, of up to 1105 N on a single attachment point. No particular concerns were foreseen on the reel.SMRT side with regards to this issue as it was assumed that the BEXUS flight encounters similar interface forces for every one of its payloads and the reel.SMRT system is no different on that account.

The summary of these forces and moments are tabulated in Table 7.1.

		Reel.SMRT forces and Moments
Vertical Forces	Steady conditions	350 (downwards)
	High acceleration conditions	2600 N (downwards)
Horizontal Forces	Maximum	1250 N (all lateral directions)
Moment	Perturbation	625 Nm
	On a single attachment point	1105 N

Table 33: Summary table of calculated Forces on Gondola prior to the flight

7.1.2 reel.SMRT EMC Effects

EMC interference between the reel.SMRT system and the gondola system was considered to be a real possibility due to the nature of motor operations. However, through careful component selection and the use of brushless motors, the EMC was minimised. Shielding was not required.

7.1.2.1 Interference

The system produces basically three main sources of interference:

a) *ZigBee modules Interference*

The frequency of the interference is at 2.4 GHz (2.408-2.480) in the spread spectrum. The power is limited in Europe to 10 dBm and the radiation pattern for the type of antenna used on reel.SMRT is shown in Figure 7.1. The figure shows relatively equally distributed radiation so the interference was expected to affect all experiments in the close proximity

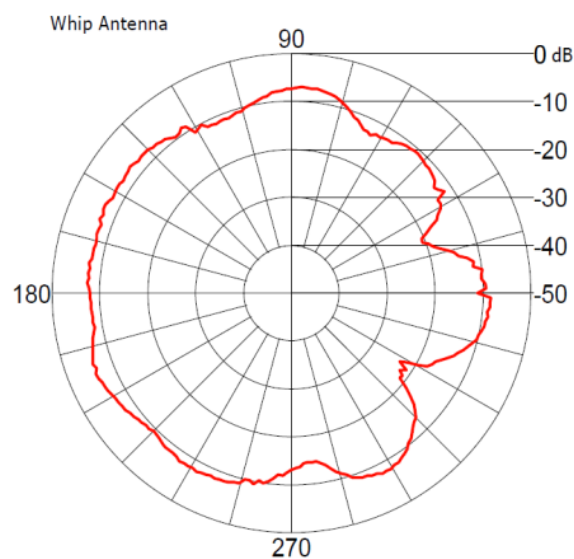


Figure 7.1 Radiation Pattern of Xbee Module

For the case that the Xbee modules were to be a source of interference, the team could easily replace the modules by the same one communicating at the frequency of 866 MHz. No problems were to be expected at this frequency. Ultimately, this change was not required as the system passed all interference tests.



b) EMI caused by switching power supplies

The system includes several switching power supplies:

1) 24/5 (two)

The frequency of the disturbance is at 350 kHz. The power supply was equipped by EMC filter as was suggested in the datasheet. The powers supply should comply to EN55022 class B.

2) 24/+12 (four)

The frequency of the disturbance is between 100 to 650 kHz. The power supply was equipped by EMC filter as suggested in the datasheet and it should comply to EN55022 class B.

In order to reduce the radiation as much as possible, the whole box with power supplies is shielded in the Aluminium box and the primary ground is connected at one point to the box. All cables connecting different boxes were twisted.

c) Motor interference

The main source of interface was expected to come from four motors located in the MAIN Payload. This type of interference, as mainly coming from the rotating magnetic field, is very difficult to minimize. The only options are to run the motor at the fastest possible speed at 100% PWM and to use brushless motors which have lowest disturbance level. Theoretically, the magnetic shielding could have be added if the interference was above admissible levels. The shielded cables were used as suggested in the datasheet of the brushless motor driver DEC50/5.

7.1.3 reel.SMRT Frequency Selection/Effects

An investigation into the frequency performance of the FISH- MAIN Payload communication system was conducted. It was determined that the frequencies of the system presented at PDR would most likely interfere with the BEXUS E-Link system. As such, the components are no longer xbee, but xbee pro 868, which transfer at 868 MHz, outside that of the E-Link. The effects to other experiments are also expected to be negligible since no other experiment was expected to use this range.

The testing was at ESRANGE was performed and the result indicated no interference between the ELINK and the BEXUS communication systems. The xbee 868 modules can be used with no limitation whatsoever. If the spare zigbee modules have to be used, the frequency channel has to be 10 or lower. Figure 7.2 shows the frequency spectrum of the zigBee modules (left peak) and the E-Link system (right peak).

The results of the interference tests run at launch week may be obtained from Section 8.5.

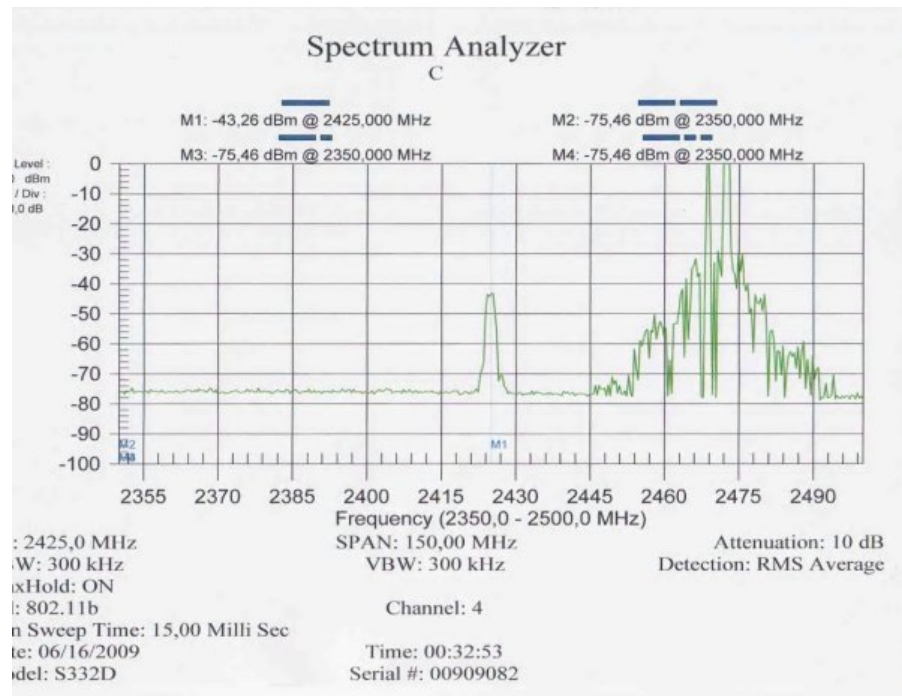


Figure 7.2: Interference test of zigbee modules

7.2 Gondola – reel.SMRT Interference

7.2.1 Gondola Perturbation Effects

There is a distinct character to the reel.SMRT experiment in the fact that a secondary payload is dropped from the MAIN payload during the experiment. This implies some requirements. First, a hole was needed in the floor of the gondola which was a square of 350 mm by 350 mm corresponding to the maximum size that the MAIN Payload can accommodate within its structure. A second obvious requirement was clearance from the bottom of the gondola. There were no problems foreseen with having simply the area under the MAIN Payload's footprint cleared of obstacles, but for prudence it was asked that as large an area as possible be cleared from a radius to the centre of the reel.SMRT experiment. To give a figure, a field of view of 45 degrees should suffice to guarantee safe operations. This was provided, with the NAVIS experiment antennae not affecting the reel.SMRT system during operations, only whipping the gondola below the system after cut-down and during descent. A third effect, raised at the PDR, was the jerk induced by the free-fall drop of the FISH. As the mass of the FISH was expected to remain within 2 kg and that the total mass of the gondola will be at least 100 kg, excluding the helium, the impact on the structure was expected to be minimum. Specifically, the force induced instantaneously as the FISH is dropped will be less than 2 % of the lift force of the BEXUS balloon. This amounts to a net lift force on the gondola of 20 N, negligible in comparison to typical perturbations during the BEXUS flight.

8 LAUNCH CAMPAIGN

This chapter encompasses all tasks to be performed and requests for resources during the launch campaign. This includes launch preparation activities, activities during the countdown, experiment time events during the flight, operational data management concept, and the preliminary FRP inputs. Furthermore, actions on recovery and post flight activities are presented.

8.1 Experiment Preparation

Experiment preparation activities that were conducted during the launch campaign prior to the gondola launch, are presented here.

The mechanical subsystem had a square hole cut into the floor of the gondola, of 370-5 mm x 370-5 mm dimensions. The mechanical subsystem shall was hence able to attach the main structure to the gondola by bolting the attachment points on the base of the MAIN Payload onto the gondola floor. This configuration is displayed in Figure 8.1 and Figure 8.2.

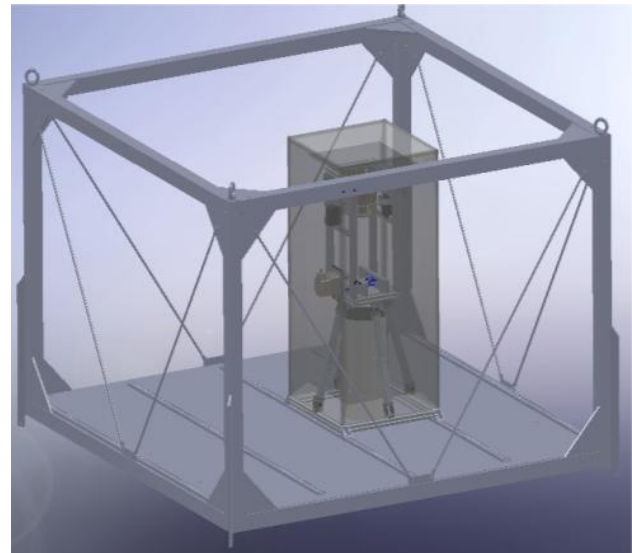


Figure 8.1 Photo of the reel.SMRT system on the gondola

Figure 8.2 The reel.SMRT system on the gondola

The electrical subsystem ran diagnostic tests on the battery voltages and the components in both the MAIN Payload and the FISH. This was comprised of the motor and sensor function tests.



The software subsystem connected the data cable from the reel.SMRT payload to the E-Link connection on the Gondola bus. The internal FISH- MAIN Payload communication was tested along with the interface to the E-Link antenna.

Once these tasks were complete, system tests were run. These comprised operating the reel and line guide through the microcontroller controls and communication systems and ensuring correct feedback through the system.

Finally, the software version on each microcontroller was confirmed to be correct by the software subsystem. The SD cards were also be confirmed as correctly installed and secure prior to installation upon the gondola.

The mechanical subsystem ensured that all mechanical switches were fastened to the correct position and locked in place. The mechanical subsystem then systematically ran through all structurally critical bolts and tightened them to ensure the stability and integrity of the structure during flight. The mechanical subsystem also confirmed that the gondola was secure and shall visually inspect the internal structure of the MAIN Payload to ensure no obstructions are in place. All objects with 'remove before flight tags' were be removed at this stage by Campbell Pegg and Mikael Persson.

The implementation of these tasks was visually confirmed and marked on the reel.SMRT pre-launch checklist by the reel.SMRT Student Payload Manager, Katherine Bennell. This checklist included such actions as positioning 'remove before flight' tags in pre-marked areas on desk. The reel.SMRT Student Payload Manager conducted a rehearsal of this checklist with the responsible members. The check was performed well with all checks working as planned.

The prelaunch checklist was followed during the launch week, and also included additional steps to those above. This comprehensive list is in Section 8.2.



8.2 Experiment Time Events during flight

A preflight checklist was finalised and delivered to the Payload Manager and ESRANGE personnel. This preflight checklist was followed and is shown over the page.

reel.SMRT Preflight Procedures

BEXUS-9 Launch Campaign

October 2009

Acronyms

CP: Campbell Pegg

FSH: FISH

JS: Jan Speidel

KB: Katherine Bennell

MJ: Mikulas Jandak

MP: MAIN Payload or Mikael Persson

NT: Nawarat Termtanasombat (Waen)

WT: Walkie-Talkie

[T-1h] PRELAUNCH CHECKLIST				
Tick Box	#	Resp.	Task	Response
Gondola: <i>KB Supervise and call</i>				
	1.1	KB	WT to GS: Power turning ON now	
	1.2	MP	MP: All power switches ON	CHECK
	1.3	MP	MP: Set brake on reel	SET
	1.4	MP	MP :Tighten screw on reel	TIGHTENED
	1.5	MP	MP: Ensure line guide is in correct position	CHECK
	1.6	MP	MP: Position line and attachment for FISH	CHECK
	1.7	MP	MP: Position base plug insulation	CHECK
	1.8	MP	MP: Ensure batteries adequately charged	CHECK
	1.9	MP	MP: Fix on insulation	CHECK
	1.10	MP	FSH: Switch on CYPRES and Confirm	ON
	1.11	MP	FSH: Confirm correct altitude on CYPRES	CONFIRM
	1.12	KB	WT to GS: Power turning OFF now	
	1.13	MP	MP: All power switches OFF	OFF
	1.14	MP	MP: Adjust focus for IP camera to long focus	CHECK
Ground Station: <i>JS Supervise and call</i>				



	1.15	NT	Startup laptop PC1	ON
	1.16	NT	Power supply CONNECTED	ATTACH
	1.17	NT	Confirm WIFI OFF	CONFIRM
	1.18	NT	Confirm Bluetooth OFF	CONFIRM
	1.19	NT	Screensaver DISABLED	CHECK
	1.20	NT	Automatic Screen Blanking DISABLED	CHECK
	1.21	NT	Connect to BEXUS via E-LINK – CONNECT cable	CHECK
	1.22	JS	WT to GO: ACK and CONFIRM Power on	
	1.23	NT	IP number check	CONNECT
	1.24	NT	Startup Ground Station Program	RUNNING
	1.25	NT	All Sensor Values GREEN	CHECK
	1.26	NT	Verify DATA TRANSFER (to memory cards)	CHECK
	1.27	JS	ACK and CONFIRM Power Supply disconnected	
	1.28	NT	Confirm gondola checklist complete	CONFIRM
Pre-launch checklist COMPLETED				
GO FOR LAUNCH ANNOUNCE				

[T-45/30min] LAST MINUTE CHECKLIST				
Tick Box	#	Resp.	Task	Response
Gondola: KB <i>Supervise and call</i>				
	2.1	CP	FSH: Activate parachute (remove safety string)	ACTIVATED
	2.2	CP	FSH: Check CYPRES activated	ACTIVATED
	2.3	CP	FSH: Turn on FSH and lock switch	CHECK
	2.4	CP	FSH: Check data is received from FSH	CHECK
	2.5	CP	MP: Attach FISH to line	ATTACH
	2.6	CP	MP : Turn on batteries and LOCK them ON	CHECK
	2.7	CP	MP: Check battery levels	CHECK
	2.8	CP	MP: Turn on IP camera and lock switch	ON
Ground Station: JS <i>Supervise and call</i>				
	2.9	NT	Startup Ground Station Program	RUNNING
	2.10	NT	All Sensor Values GREEN	CHECK
	2.11	NT	Verify DATA TRANSFER (to memory cards)	CHECK
	2.12	NT	Confirm gondola checklist complete	CONFIRM
End of Last Minute Checklist				



LAUNCH				
Tick Box	#	Resp.	Task	Response
Ground Station: NT Operator (Computer 1 – GS) JS Assistant Operator (Computer 2 – IP Camera)				
	3.1	NT	Monitor GPS position data on Moving Map Display	MONITOR
	3.2	NT	Monitor Temperature measurements in FISH and MAIN Payload	MONITOR
	3.3	NT	Check behaviour of automatic temp. control mechanism	CHECK
	3.4	NT	Change to high data rate mode to check the high data rate ability for drop	CHECK
End of Launch Checklist				

[T+X mins] REACH FLOATING ALTITUDE				
Tick Box	#	Resp.	Task	Response
Ground Station: NT Operator JS Assistant Operator				
	4.1	NT	Check temperature ranges still GREEN	MONITOR
	4.2	NT	When CLEARED TO DROP (by Esrange personnel), rotate reel into correct position	MONITOR
	4.3	NT	Start IP Camera Recording	CHECK
	4.4	NT	Open Line Guide	OPEN
	4.5	NT	Do a short drop (~700ms)	CHECK
	4.6	NT	Transfer data to MAIN Payload	CHECK
	4.7	NT	Transfer data to GS	CHECK
	4.8	NT	Estimate distance from gondola using IP camera as required	CHECK
	4.9	NT	Monitor motor temperature	MONITOR
	4.10	NT	Wait until next cleared to drop to repeat steps 1 to 6.	MONITOR
End of Floating Altitude Checklist				

[T+~ 4h] JUST PRIOR TO CUT				
Tick Box	#	Resp.	Task	Response
Ground Station: NT Operator JS Assistant Operator				
	5.1	NT	Prepare for landing: line guide	MONITOR



	5.2	NT	Transfer all data from memory card to GS	MONITOR
	5.3	NT	Take pictures and video using the IP camera	CHECK
End of Pre-Cut Checklist				

A diagnostics flowchart was also written, which aimed to facilitate rapid actions on any system failure occurring within the system during the flight. Such diagnostic understanding was made possible as a result of the extensive testing and problem solving on the system that occurred just prior to and during launch week. This flowchart was utilised during the flight when the FISH was lost to good effect, and enabled the team to act in a rationale, calm and effective manner. It was colour coded for ease of navigation.

Symptoms	Problems	Actions
TASK LINE GUIDE		
- Movement - Watch to see if comes back up - Look at swing (lever length)	Overshoot	1. view the line guide 2. Reel back slowly 3. Try and reel up: If not work, line guide still done up (if only done up 1/2 cycle it may still move through anyway)
TASK DROP (ensure audio on)		
DOES NOT DROP		
- FISH does not drop- maybe moves once - May hear the servo move over audio	Positioning of bail is not correct	1. Try Again, reeling up slowly between reel ups
- IF does not work: and the FISH probably doesn't move much at all	Line Guide locked	1. reel up the line a small amount & Go to LINE GUIDE
- Temperature very low	Motor not working OR Servo not working OR batteries dead	1. Keep trying to warm up the system
DROPS OUT OF SIGHT		
- Keeps falling on IP camera and FISH goes out of sight	Camera not high res enough OR FISH LOST	1. Turn Reel



		2. Go to high resolution 3. View line to see if slack or tight 4. See if we get data from the FISH and analyse it
--> IF FISH Fallen off	FISH LOST	1. JAN: "LOST FISH" 2. KATHERINE: take time from countdown clock 3. KATHERINE: Ask to mark GPS position 4. KATHERINE: Ask for windfield info 5. Try to reel up the line if not already 6. WAIT 30sec- 1min 7. Reel up in 1 minute lots to let motor cool
-->IF not reeling up after 10 mins	Servo jammed or bail system damaged	1. reel up the line guide
--> IF FISH IS THERE	reel up system didn't work	1. WAIT 30sec- 1min 2. Reel up in 1 minute lots to let motor cool
--> IF not reel up after 10 mins	Servo jammed or bail system damaged	1. reel up the line guide
DROPS and JAMS at the end (FISH VISIBLE)		
Keeps falling on IP Camera FISH visible at the end of the line Does not reel up		1. WAIT 30sec- 1min 2. Reel up in 1 minute lots to let motor cool 3. reel up the line guide
-->IF not reel up after 10 mins	Servo jammed or bail system damaged	1. reel up the line guide
SLOW REEL		
FISH doesn't move		1. very short reel up
IF NO movement	line guide still locked	1. fix line guide
IF Movement	switch not working	1. stop slow reel and resume other operations
FISH moves and doesn't stop	cannot switch it back	1. try again
IF this still doesn't stop	switch back not working	1. Use line guide to reel up

Table 34 Flight Diagnostics Table: otherwise known as 'The Don't Panic! Checklist'

The experiment started recording data when it was turned on as a final step before launch. The experiment stopped recording data once it lost power and communications. During the flight, it was desired that a minimum of 10 drops and 3 slow reels were to be performed, however, only one drop took place and the FISH was unable to be recovered. The first stage was to unlock the line guide,



then reel the FISH back up. The first operational mode was the drop mode to ensure the demonstrated operation of all the primary objective, as there existed a slight risk that the slow reel mode could fail due to the single point error of the servo on the bail switch.

The key events that took place during the actual flight are tabulated in Section 8.8.2.

8.3 Operational Data Management Concept

All sensor data generated during the experiment was stored locally on SD-Card flash memory. In addition, all data was also downloaded to the ground station to save the data in case the gondola could not be recovered.

The data rate from the FISH to the MAIN Payload is greatest during the drop tests. During that time it can reach up to 180 kBit/s. The data rate of the downlink to the ground station will never reach a value of more than 20 kBit/s. This in fact was not exceeded, as there existed an error in the software which prevented the high data rate values from being transmitted to the ground station. This meant that no data was recorded for the drop. However, the high data rate acceleration data from the FISH was recorded on the FISH SD card. This means that the FISH SD card holds valuable data for its fall throughout the atmosphere, characterising the quality of low gravity in freefall. As the FISH has not yet been found, this data has not been able to be recovered, at the time of writing.

The data generated by the camera was tested during the interference test at Esrange. A rough estimate of the manufacturer is 100 kByte/s when in video mode (movie). But most of the time only one still image every 10 seconds will be sent. In case the bandwidth is needed for other experiments a lower image resolution can be selected or, if necessary, the camera can be switched off remotely from the ground. During the flight, the camera was able to be operated continuously as it was deemed to not affect the data from the other experiments.

The ground station software was directly connected to the balloon transmission system (E-Link) via Ethernet. It provided status and sensor data so that the current state of the experiment could be seen at all times during the flight. In addition, all data downlinked from the balloon was stored on the hard drive of the Ground Station PC for post-processing. It was possible to transmit telecommands from the ground station to the experiment in case an unforeseen event occurs. By sending certain tele-commands, the experiment can recover from a temporary malfunction and continue the flight without a degraded experiment. This was not required during the flight.

However, by storing the most important sensor data at three different locations, the probability of a total loss of the most precious data was anticipated to remain very low. However, it was found upon the countdown list on the morning of the flight that the wrong software version had been loaded into the MAIN Payload



microcontroller. Only one key line in the software differed from what was required – the consequence was that the high data rate mode data was unable to be transferred to the ground station and instead remained stored on the FISH. This meant that data from the FISH was sent to the ground station until the DROP command was given. As the high data rate mode commencement was tied automatically to the drop command, this was not fixable from the ground station.

8.4 Experiment Acceptance Review – EAR

Reel.SMRT had the advantage of constructing the experiment in Kiruna and had the benefit of being able to bring the experiment to ESRANGE before the flight campaign to continue to integrate and test systems including the interference test, EMC test and interfacing structurally with the gondola. This allowed reel.SMRT the ability to pass the EAR, despite the complexity of the system and the extensive last minute testing this necessitated.

8.5 Mission Interference Test – MIT

The MIT is of importance to reel.SMRT as not only did EMC effects need to be investigated but so also did the communication between the MAIN Payload and the FISH. The prime function of this test was to ensure that there was no interference with the balloon systems but this was also be a good opportunity to test the intra-experiment communication. A preliminary interference test was conducted and passed in June at ESRANGE with both Xigbee and Xigbee Pro models.

An indoor practise interference test was performed at Esrance for BEXUS-9. reel.SMRT was able to pass this test without complications or problems. No system was interfered with in a manner that jeopardised the mission. NAVIS received some interference from our motors running during the drop, however as we planned to drop for only a short percentage of the flight, this was deemed acceptable. To reduce any risk to the NAVIS mission, in case of our motors stalling for example, they were allowed 10 minutes of operation before reel.SMRT commenced our first drop of the flight.

The MIT was conducted the day after the practise interference test. This test did not go smoothly, however. This is because the ground station was not receiving a signal from the FISH and it was unclear at what point in the communication links the system broke down. The Payload Manager deemed that if reel.SMRT could demonstrate that both Zigbees were operating (transferring data to and from the FISH and the MAIN Payload) that the interference test could be run. To prove that the Zigbees were operational despite the loss of data, electronic sniffers were used, courtesy of DLR. Figure 8.3 and Figure 8.4 demonstrate the use of this 'sniffer', and the working Zigbee signal recorded on it. reel.SMRT thus passed the MIT.

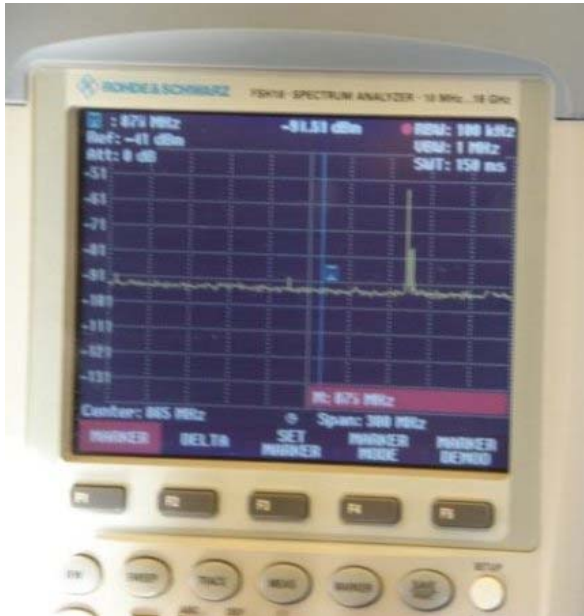


Figure 8.3 The electronic device used to demonstrate Zigbee operation during the MIT



Figure 8.4 The testing of the Zigbee communication performance prior to the MIT

8.6 Launch Readiness Review – LRR

The launch readiness review was conducted following the FRR and MIT to examine the readiness of the experiment to begin the launch. Due to the delay in the launch date due to weather conditions, reel.SMART was able to pass the LRR, despite all of the issues and solutions that were implemented during the launch week. Approximately 48 hours before flight, reel.SMART was ready for flight, and made no further modifications to its systems.

8.7 Inputs for the Flight Requirement Plan - FRP

The inputs for the requirements plan were as follows:

Dimensions and Mass of Experiment Components

400 x 400 x 850 mm

17.8 kg estimate (possibly up to 20 kg)

Possible Identified Risks

There were concerns raised by the team about the risks of PCM (protection circuit) and balance intelligent charging of the MAIN Payload batteries prior to the MTR. The PCM was unavailable with the batteries most suited to the



reel.SMRT design and budget. It was understood by the team that a PCM was not required, but that the intelligent charger (as accompanies the selected batteries) was more critical. The problem was that the PCM does have functionality involving minimal voltage and maximum current: the voltage on the battery should not be lower than a certain level. If this such a scenario was to occur, the battery pack has the risk of becoming unstable and the slight risk of exploding during the next charging (this happened to one of the previous BEXUS teams from the Czech Republic). With the intelligent charger, the team does not believe that the PCM is required as long as care is taken not to charge the batteries too deeply. However, a problem with minimal voltage could occur following the mission, as the batteries will have a very small discharge whilst the gondola is collected and brought back to ESRANGE.

Following consultation with ESRANGE, Olle Persson and the ESRANGE Safety Board Chairman requested that if the PCM solution is not possible, that the team should write a procedure for battery handling, storage, placement in the gondola/experiment that ensures there is no risk for any personnel. This included the whole chain, from the lab at LTU to the preparations hall, launch, recovery, disassemble and disposal. This document was written by Mikulas Jandak, the member responsible for the MAIN Payload Electrical Subsystem, and checked by Katherine Bennell, the reel.SMRT Project Manager. This document was provided to ESRANGE in mid- September.

During the final testing of the system, the batteries became critically discharged, despite team members regularly checking the battery voltages during testing. To ensure no risks of injury occurred, these batteries were not recharged, in accordance with the battery handling procedure written by reel.SMRT and approved by ESRANGE. This necessitated the purchase of new batteries and chargers which were able to be incorporated into the reel.SMRT system during launch week. reel.SMRT also recommended in the flight recovery procedure for ESRANGE personnel recovering the gondola to turn off the batteries. Unfortunately this did not occur and so therefore the second set of batteries became critically discharged also, and so therefore were disposed of for safety reasons.

All other risks identified were been mitigated.

Refer to Section Section Risk Management 5.5 for other risks identified and mitigated.

Electrical Interface

There were 2 electrical interfaces, one is of reel.SMRT MAIN payload E-LINK connector, the other is IP camera E-LINK connector.



Power Consumption

Power is supplied by the experiment system.

Fish: ~0.9W.

MAIN Payload: 70 W peak, 14 W average; the average value will slightly increase due to the use of heaters. The exact number will be known after the final whole-system test is run and thermal effects can be properly determined.

Telemetry (Downlink, Uplink)

Downlink and uplink using the E-Link system are required for experiment control.

Special Requirements (Experiment preparation, calibration, tests)

reel.SMRT requires late access to the balloon gondola to allow for testing.

Timeline for mission preparation and post mission activities

Delivery - 21 September at the latest (by car from Kiruna)

Integration – Initial integration in August where possible, Early September

On Site Testing – September where possible, Launch week

Returning of Experiment - End of launch week (by car to Kiruna)

8.7.1 Requirements on Laboratories

reel.SMRT did not originally foresee any laboratory access. However, the personnel at ESRANGE kindly assisted the team with solutions for electrical problems encountered during final testing on the FISH PCB.

8.7.2 Requirements on Integration Hall

The team requests tables and chairs as sufficient for each of the seven members of the reel.SMRT team to work in the integration hall. Access to power and the internet were also required for the project and were provided.

8.7.3 Requirements on Trunk Cabling

There were no requirements on trunk cabling.

8.7.4 Requirements on Launcher

reel.SMRT was able to be located anywhere on the gondola but the preference was to be located in the centre to reduce perturbations induced on the experiment. This was provided for reel.SMRT.

8.7.5 Requirements on Blockhouse

Within the blockhouse, the team required an area for mission control of the reel.SMRT payload. This was to be comprised of:

1. Two stations for laptops (team's own laptops), including at least 3 power points. One laptop comprises the primary ground station, the second shall



comprise the back-up ground station. Another will be used for analysis of flight data for trouble shooting.

2. As the ground station was used for uplink of commands and downlink of requested telemetry data, the team also requested access to relevant reel.SMRT data down-linked from the balloon and also the capability to uplink to the balloon from these computers.

3. Desk space and seating for seven team members in close proximity to the ground station.

These requirements were provided for.

8.7.6 Requirements on Scientific Centre

There were no requirements on the scientific centre.

8.7.7 Requirements on Countdown (CD)

reel.SMRT required the E-Link connection during countdown to run diagnostic tests on the system. In order to confirm these tests and conduct other important tasks, the team required late access to the payload as detailed in Section 8.2.

8.7.8 List of Hazardous Materials

Potentially hazardous materials that were to be flown on the reel.SMRT payload only included batteries. There were no explosives, radioactive sources or hazardous chemicals present on the reel.SMRT Payload.

8.7.9 Requirements on Recovery

The recovery procedure required is of the 'normal' mode. Special requirements exist for the purpose of retaining access to data and data integrity and to minimise damage to the hardware.

The requirements include:

1. All hardware of the payload is requested to be returned. The components of highest priority are the SD Cards of the FISH and of the MAIN Payload.
2. There is no requirement for extracting the FISH from the MAIN Payload.
3. There is a potential requirement to disconnect the batteries from the main power subsystem so that the batteries will not be fully discharged and hence damaged (refer to Section 8.7 *Possible Identified Risks*).

The detailed recovery checklist was provided to Esrange personnel in both Swedish and English and was discussed with the recovery personnel prior to the flight. This checklist may be obtained from the Appendix 2.

reel.SMRT Postflight Procedures

BEXUS-9 Launch Campaign

October 2009

reel.SMRT FLIGHT RECOVERY PROCEDURE (T+ ~1d)

To be performed by: ESRANGE Recovery Personnel

Items provided by reel.SMRT to the ESRANGE Recovery Personnel:

- i. Box for collecting equipment during recovery
- ii. One flathead screwdriver
- iii. One Allen Key

Items to be returned in addition to the gondola for the reel.SMRT Project:

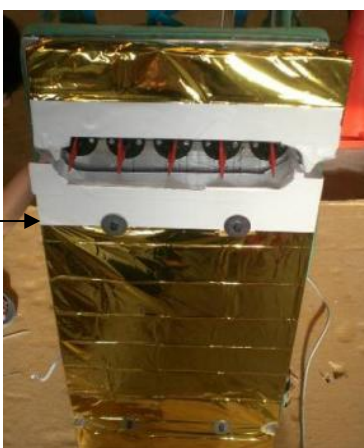
- i. The FISH and;
- ii. Four red power switches/keys

STAGE 1 - Power OFF Procedure

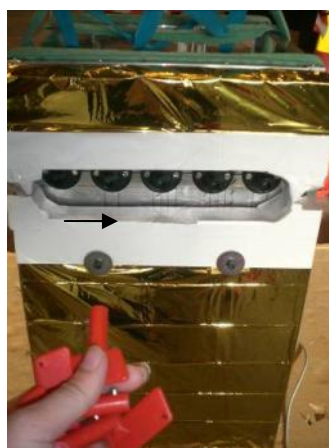
1. The reel.SMRT power switches are located on the same side of the gondola as the solar panel. Only the 4 leftmost switches are plugged in and are turned on (not 5 as shown below). The first picture shows how the experiment should look when found.



Step 1



Step 2



Step 3

2. Turn all of the switches to the vertical position by turning the left one off first and moving along them from left to right. This should then look as in the second picture (this may require the string connecting them to be cut). Turning the switches to the vertical position turns off the batteries. If the batteries are disconnected and off, the switches shall be able to be removed.

3. Remove the switches and bring them back to ESRANGE in the box provided. There should be 4 switches in total.

STAGE 2 – SECURE THE LINE



The reel.SMRT system has a green thin fishing line hanging from it out of the hole in the center of the gondola, attaching it to the 'FISH'. This line needs to be cut to prevent any danger to the gondola during transportation.

1. Remove any side insulation panel on the reel.SMRT Payload, by unscrewing the wingnuts below using the Allen Key provided. The easiest side to remove is that in the middle of the gondola as shown below. To remove it, unscrew the wingnuts on the sides of the panel (not the four nuts in the middle of the panel with the big washers).
2. Using scissors, cut the green line and tie it off to any part of the structure.
3. Replace the insulation panel.

STAGE 3 - LOCATE THE 'FISH'

When recovering the FISH, always keep the end of the tube pointed away from all personnel, due to the risk of the parachute deploying.



Locate the FISH (shown on left) by searching for it in the most likely places for it to be. There are 5 places where the FISH may be. These are:

- a. Within the Gondola within the reel.SMRT Payload
- b. Under the Gondola
- c. In the near vicinity of the gondola and connected to the gondola through the hole in the floor under the reel.SMRT payload by a thin green Dyneema fishing line.
- d. In the near vicinity of the gondola and not connected to the gondola (the line has snapped)
- e. Not in the vicinity of the gondola (lost during the flight)

If a. or b. then:

- i. The FISH will not appear to be in the vicinity of the gondola.
- ii. When the line is cut, the FISH may have been visible within the

gondola.

iii. When the gondola is lifted up, the FISH may be visible underneath or from underneath the gondola.
If c. then:

- i. Follow the line from the FISH to the gondola or vice versa. Cut the line near the gondola and collect the FISH.

If d. then:

- i. Obtain the FISH, ensure the line from the gondola is not extending far beyond the gondola. If so, cut the line.

If e. then:

- i. Ensure that there is no long length of line dangling under the gondola, if it is, cut it off.

STAGE 4 - TURN OFF CYPRES UNIT

If the time between launch and recovery exceeds 14 hours then the CYPRES is already off.

If the time between launch and recovery is less than 14 hours then the CYPRES must be deactivated.

To deactivate the CYPRES unit:

1. Use a flat-head screwdriver to unscrew the four holes on the side panel as shown (note that the FISH is painted ORANGE not grey).
2. Open the side panel, the CYPRES should be visible inside.
3. Insert your fingers and pull out the silver unit of the CYPRES



4. To turn the CYPRES unit off, conduct the following procedure:
 - i. **CLICK** (not press) the CYPRES Unit button once, quickly
 - ii. Wait
 - iii. A red light will illuminate
 - iv. Immediately **CLICK** when you see the light
 - v. wait
 - vi. Another red light will illuminate
 - vii. Immediately **CLICK** when you see the light
 - viii. wait
 - ix. Another red light will illuminate
 - x. Immediately **CLICK** when you see the light
 - xi. wait
 - xii. No light should illuminate and the screen should go blank. If it does not, redo the sequence from i. to xii.

Notes on turning the CYPRES off:

- The off-sequence is very specific and may require a number of attempts to get the timing correct.
- 'Click' rather than 'Press' the button very sharply and rapidly. After the first click, remain poised and ready for the next click, and 'click' as soon as the red light illuminates.
- If you are still unable to turn it off, there is a risk of the parachute deploying in the helicopter. In this case, ensure that the box provided is used and that the parachute is not in the vicinity of anything it can damage during the transportation.

STAGE 5 - RETURN FISH TO ESRANGE

The FISH should not be stored in the cabin of the helicopter, but rather in the baggage section away from all personnel and placed in the box provided. This is due to the potential danger of the CYPRES unit causing the parachute to go off, which if pointed towards someone could cause harm.



THANK YOU !

8.7.10 Consumables to be Supplied by ESRANGE

There were no requests for consumables to be supplied by ESRANGE.

8.7.11 Requirement on Box Storage

It was requested that the reel.SMRT Payload be stored upright and with care as a 'fragile item'. This was to minimise the FISH impacting upon the internal structure and tangling of the tether. The payload should also be stored in a cool (approximately room temperature), dry, indoor area. The approximate volume of the box was given to be 0.5 m x 0.5 m x 1 m, with the longest dimension being in the vertical direction.

8.7.12 Arrangement of Rental Cars & Mobile Phones

Each team member carried their own mobile telephone and therefore there was no need for additional mobile phones to be provided. Prior to the launch week, a contact list was distributed to the team by the Project Manager including the phone numbers of all relevant personnel.

No rental cars were required, as all team members were kindly able to be sponsored and accommodated at ESRANGE.

8.7.13 Arrangement of Office Accommodation

There was no necessity for the arrangement of office accommodation.



8.8 Launch Campaign

The launch campaign was involved the completion of testing of the reel.SMRT system, a challenging process which involved the solution of many problems and rigorous work.

Ultimately, the experiment demonstrated full functionality of all systems and then passed the MIT and EAR and flew in this condition. The experiment however, during the flight did not reach full functionality for reasons covered in the diagnostics section.

8.8.1 Flight Preparation During Launch Campaign

On the mechanical side, several tests were performed during the launch week in preparation for flight. Using the crane in the cathedral and in the MAXUS tower, the experiment was raised up to 6 m to 12 m in the air in order to perform several full system tests on reduced length drops. Many system tests were performed with reduced loads because the team was monitoring the condition of the reel and determined that it was wearing out fairly quickly and that not so many tests would be possible. Several critical issues were solved during those tests, including setting the brake on the reel to a proper level, securing the interface of the line to the reel and to the FISH, determining reasonable line length on the reel (~70 m) and maximum drop length (~30 m), as well as some thermal regulation issues.

8.8.2 Flight Performance

During the flight, the mechanisms of the MAIN Payload were largely successful. An image of the FISH below the gondola is shown in Figure 8.5.



Figure 8.5 IP camera image looking down at the FISH

Firstly, the line guide mechanism was able to secure the FISH without any visible disturbances and it was operating as expected, releasing the line to be ready for a drop. The reeling-up operation was also successful in that it was able reel the FISH up for about 50 cm to put it in a good position pre-drop. Also, the bail release mechanism worked and successfully released the FISH into a free-fall which was, according to visual feedback of the video, of very good quality, beyond expectations. The reel motor or bail closing mechanism failed to work as the drop was never stopped, this could be either a failure of the line, the bail closing mechanism, or the reel motor; the diagnostics are presented in the following sections. Finally, the thermal regulation of the components showed remarkable performance as all temperature readings were well within operating conditions and were able to recover from an initially low temperature before powering up the experiment on the launch pad. This thermal performance is demonstrated in Section 8.10.1

However, it was found upon the countdown list on the morning of the flight that the wrong software version had been loaded into the MAIN Payload microcontroller. Although there was time to change the flight software, it was deemed to risky to dismantle the experiment to do so. Only one key line in the software differed from what was required – the consequence was that the high data rate mode data was unable to be transferred to the ground station and instead remained stored on the FISH. This meant that data from the FISH was sent to the ground station until the DROP command was given. As the high data rate mode commencement was tied automatically to the drop command, this was not fixable from the ground station



The experiment time events during the flight are shown in Table 35. The ground station was also filmed during the flight for any required diagnostics, however this was not required. The experiment time events correlate well with the prelaunch checklist and the diagnostics checklist presented in Section 8.2.

The procedure of Table 35 deviates slightly from the theoretical procedure presented in Section 3.3. The key deviation is that instead of reeling down the FISH over the entirety of the line, the drop mode was executed first during the flight, after line guide operation was demonstrated. This change was implemented in an attempt to avoid potential problems due to a single point failure of the bail switch. The switch is used to change between the reeling down and drop modes and it was deemed more desirable to first demonstrate the drop, our first objective, before meeting this risk.

Time on count down clock	Count on countdown clock	Task	Symptom	Diagnosis	Action	Consequence
5:44:25	T-2h	FISH turned on	Low data rate from FISH	Bug in MAIN Payload Software	Search through software - found it to be a single line different between versions	High data rate doesn't work but all the data is stored on the FISH
8:25:25	T-50m	FISH attached	Seen through IP	Check # LG turns	Campbell took photo as part of the prelaunch checklist, looking up at the MAIN Payload after attaching the FISH.	Know # of turns and analysis by waen/ jan
9:13:25	T-1m (stalled)	Lost comms with FISH	Seen on GS	Either Xbee or Fish too cold, or E-LINK/EBASS issues	Try and regain comms	No high data rate to record data on the FISH, lost comms with FISH, unknown if FISH is recording data at all.
9:33:22	T-0m	Launch				
9:33:25	T+3s	Regained comms with FISH	Seen on GS	FISH sending data as desired to the ground station, therefore FISH recording data onboard SD card	Cheered Loudly	FISH recording valid data



11:00:25	T+1h27m03s	Float - 10 minute warning	Mikael Inga announced it	-	10 min warning	Reread diagnostics checklist and action plan
11:15:35	T+1h42m13s	All clear for drop	Mikael Inga gave permission	-	Confirmed all systems working well and in correct temp ranges on GS	Ready to drop
11:15:45	T+1h42m23s	Waen announced 'prepare to drop'	-	-	-	Silence in the room, large crowd around video monitor
11:15:53	T+1h42m31s	Line guide opened correctly, reel up sequence worked correctly	Viewed on IP Camera	Systems working well	Cheered Loudly	-
11:16:27	T+1h43m05s	DROP	Waen clicked Drop command on GS	Drop confirmed on IP Camera, appeared smooth, drop operated correctly	Observed	-
		Observe	Loud clicking sounds over audio lasting approx. 2 seconds	The bail did not close as designed. FISH most likely not caught correctly	Continued to observe	-
11:16:41	T+1h43m19s	Confirmed dropped out of sight by all 3 member in ops team	Could not see the FISH in the IP camera	But this can be hard to see	Followed Diagnostics Checklist	-
		sent reel up command	Could not see any line on the IP camera	But this can be hard to see	Informed Mikael Inga of possible lost FISH	-
11:17:16	T+1h43m54s	DROP command again to see if servo has moved	The servo was heard audibly	The servo would have operated during the DROP and not got stuck	Continue to reel up any potentially dangling line for safety purposes	-
		sent '10000' degs reel up command	The FISH did not come into view, no line was visible	The FISH was no longer on the line	Called 'LOST FISH', informed Mikael Inga	reel.SMRT system end of dropping and reel operations
Until the end of the flight and lost comms		Kept IP Camera running with audio	-	-	Commenced diagnostics analysis of IP camera footage on second ground station computer and TV screen	The system was shown to maintain structural integrity from the IP camera data during descent after cut-off

Table 35 Key reel.SMRT events during the flight of BEXUS-9 as recorded during the flight

8.8.3 Recovery (Condition of experiment)

The condition of the experiment was poor upon it being opened, which necessitated a particularly careful disassembly to aid diagnostics. The structural

bolts and screws had loosened or come undone, and the line guide was broken off. As the IP camera data showed structural integrity throughout the flight until communication loss just prior to landing, it was assumed that the damage to the structure occurred during landing, recovery or transportation back to ESRANGE. Figure 8.6 demonstrates how the structure had lost its integrity. The blue cable was being attached for reinforcement to lift the system out of the gondola.

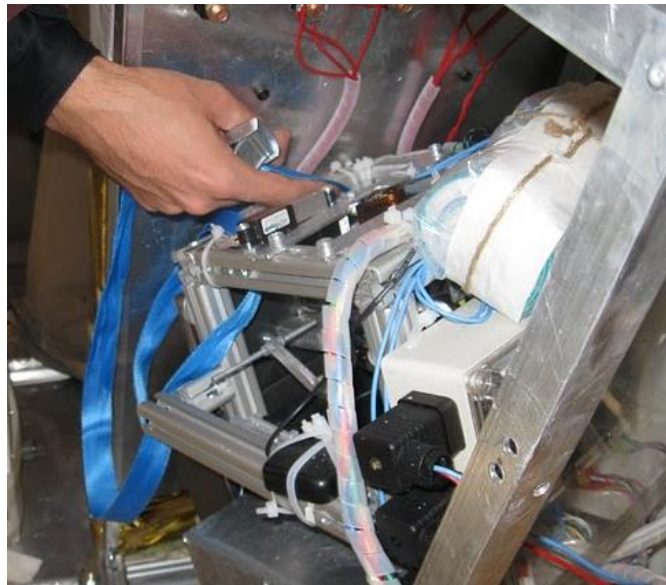


Figure 8.6 Experiment after return to ESRANGE

8.8.4 Post-flight Activities / Operations

After the payload was returned to the cathedral, the Project Manager opened the system. As the experiment did not achieve full functionality, the system was removed from the gondola and dismantled carefully, with photos taken of each step and each step recorded. These steps are described in Section 8.9.1.

SD cards containing the data were recovered by the member responsible for the data, Jan Speidel, under supervision of the Project Manager, Katherine Bennell. Jan Speidel shall then compare the data to that transmitted over the E-Link connection.

The MAIN Payload, FISH and all other equipment was returned to Kiruna by car at the end of the week by Jan Speidel and Nawarat Termtanasombat.

The team then returned to their home countries, where they conducted an analysis of the data to determine the validity of it in determining the performance of the system in relation to the reduced gravity environment.

With the assistance of ESRANGE personnel, the projected trajectory of the FISH was calculated, using the ESRANGE trajectory calculation software and the time of drop recorded. This enabled estimations of the ground impact position of the

FISH for different heights of parachute deployment. The parachute CYPRES system was set at 440hPa, corresponding to an altitude of deployment of 4250m.

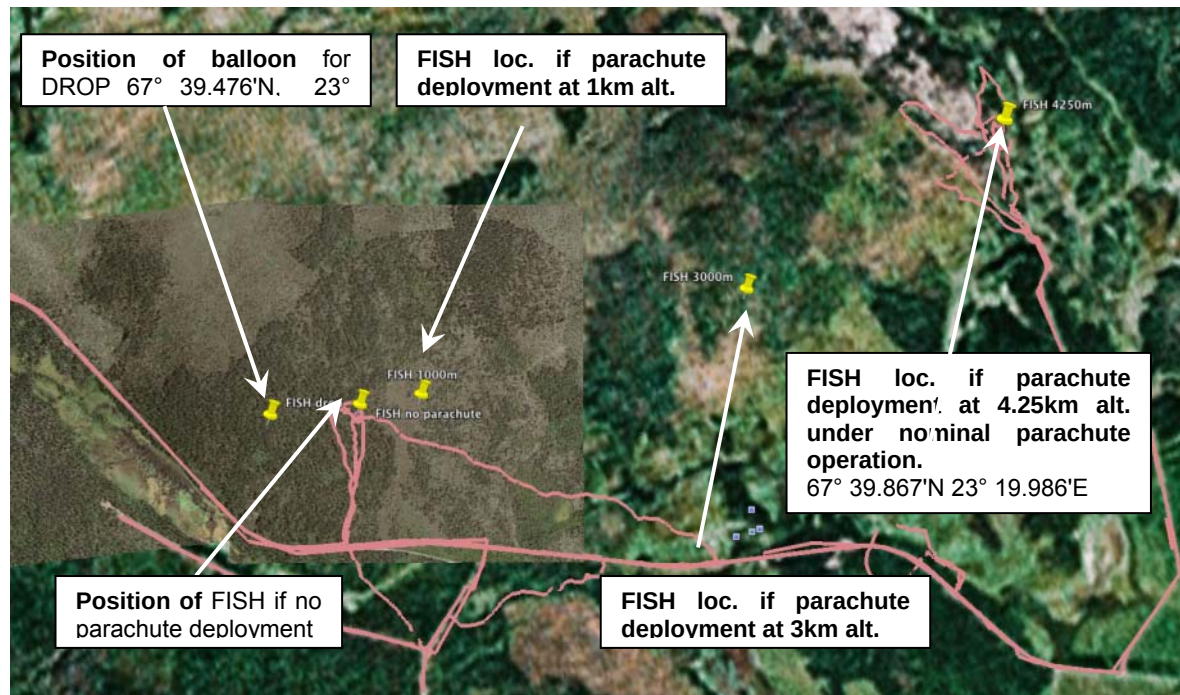


Figure 8.7 Potential landing sites of the FISH calculated with ESRANGE trajectory analysis. The locations marked by yellow pins and the arrows correspond to different heights of parachute deployment. The rightmost point is the location if the parachute opened as expected from multiple successful deployment tests. The pink lines represent the path of the team members on their search for the FISH. The approximate distance between the position of the balloon when the FISH was dropped to the rightmost marker is 4.5 km. The overlay pictures were sourced from www.hitta.se)

The two reel.SMRT members living in Kiruna consequently travelled to Northern Sweden to attempt to locate the FISH. Their search paths are shown in Figure 8.7 in pink. Unfortunately the ground colours at the time were bright orange, the colour of the painted FISH that the team had thought would be distinguishable against the snow and background foliage. This is demonstrated in Figure 8.8.



Figure 8.9 A search for the FISH – unfortunately the ground foliage matches the psychedelic orange paint of the FISH, designed to stand out on snow and greenery!

These members have now made two trips to the location in Northern Sweden, near the Finnish border, and have not yet located the FISH, despite searching in defined search patterns. It is hoped that the sticker on the FISH should direct anyone else who finds it to contact ESRANGE.

Once these tasks were completed, the team reviewed the performance of the project and produced this final report. The next step is to write a paper and develop a poster about the system for a relevant conference or journal and continue to seek out the FISH where possible.

8.9 Diagnostics and Analysis

When the gondola returned, a thorough investigation was performed on the experiment.

The IP camera steady position and unobstructed view demonstrated that the structure retained its integrity throughout the flight phase until loss of connection just prior to landing. Therefore, due to landing forces or rough transport to the base, several critical construction screws were dislodged despite the use of lock-tight. This thus made narrow point of fault analysis almost impossible. However, the line perforation indicates the abrupt cut-off the line, supporting the hypothesis of the breakdown of the critical connection point.



All further data and electrical connections such as circuit boards, temperatures sensors, wiring and so on appears intact throughout the experiment, as indicated through evidence of the IP camera sound and video. For example, the servo, line guide, reel motor all operated correctly according to our audio and visual diagnosis.

8.9.1 Approach to Diagnostics and Analysis

After the recovery of the MAIN Payload, the physical diagnostics and analysis of the failure that occurred within the experiment started. The approach was to use all available data from the flight, that is, the temperature readings during the flight and during the drop as well as the audio-video recording of the drop. Also, careful inspection of the recovered payload was necessary to examine the physical evidence of the failure. During the time spent waiting for the recovery team to bring the gondola back, the footage of the drop was examined and re-examined several times to identify the evidence that it showed. Then, as the MAIN payload was accessible to the team, after all other teams had recovered their own experiments, we were able to ascertain the condition of the payload. Careful measures were taken to document the process of recovering the payload, partially disassembling it, and examining critical components.

The key steps taken were as follows, with photos taken for each step:

1. The batteries were immediately turned off before two sides and roof insulation were removed. The other two were left there to insure the structure did not collapse.
2. The system was viewed in order to notice any irregularities. The system was partially collapsed, however initial observations showed the line had snapped, and this line was wound up to the reel. The line was also snapped on the attachment to the reel. The servo still appeared fine. The brush motor connection was bent and the line guide fell out of the system onto the truck transporting the system to ESRANGE.
3. Support straps were attached to the top of the system, to enable it to be supported vertically. The top metal plate was unscrewed and the crane was then used to carefully lift the structure. During lifting, it was observed that the reel motor was broken.

4. The system was moved to the reel.SMART bench where the frame and side panels were removed.



Figure 8.10 Post-Flight Handling of the MAIN Payload with a crane



Figure 8.11 Post-Flight Examination of the MAIN Payload, in the picture (left to right) are Koen de Beule, Mikael Persson, Katherine Bennell, and Nawarat Termtanasombat.

5. The batteries were then removed.
6. Two screws were found in the gearbox. This damaged was assumed to be postflight, as the FISH was reeled up during the flight and therefore the motor was operational.
7. The battery connectors were then unscrewed in order to measure the battery voltages. Battery 1 had a voltage of 13 V and Battery 2 had a voltage of 9 V and therefore both batteries were critically discharged.
8. The IP camera was removed by cutting the IP camera wires. The IP camera appeared to be undamaged.
9. The gear box was taped up and the linear motor unscrewed.
10. It was noted that frayed bits of line were distributed throughout the system, that the line was stuck to the bail.
11. The reel was then removed and analysed.
12. Photos were taken of the rest of the system.

8.9.2 Condition and Evidence (the line broke)

Flight data showed that all monitored components were well within operating temperature ranges, mainly between 0 and 10 degrees Celsius for the experimental phase. Hence, thermal issues on the electrical components were regarded as a highly improbable cause for the failure. Then, the footage of the

drop clearly demonstrated that the unlocking of the line guide was successful, that the reeling up of the line was working as expected, and that the bail was released to drop the FISH. Also, from the audio, it was quite certain that the bail closed eventually, because operating the reel after the drop did not generate a noticeable difference to the initial operation of the reel. Moreover, the audio lend us to believe that the bail closing operation took much longer than expected and that several awkward sounds were recorded which suggests both difficulties for the reel motor to overcome the force necessary to close the bail and harsh frictional events between the line and the bail itself.

Figure 8.12 shows the magnitude and durations of these sounds, which may be seen to extend over greater than two seconds. That the FISH was still exerting forces on the gondola for greater than three seconds after the drop commenced is indicative that the line did not just snap immediately upon attempting to close the bail, nor just ran to the end of the 70 m line and snapped off.

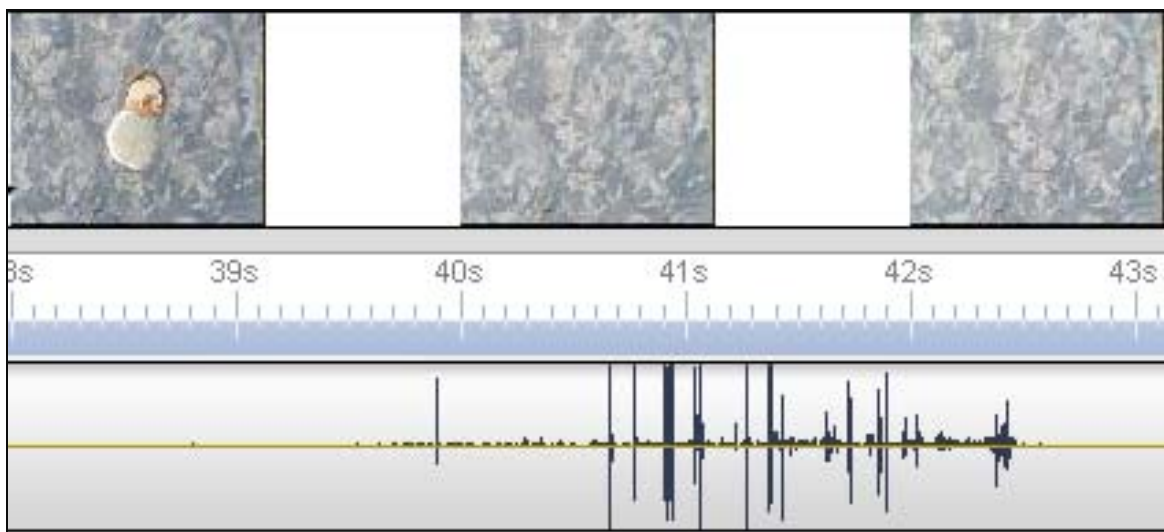


Figure 8.12 Audio graph from the FISH drop video. The FISH drop video may be found http://www.youtube.com/user/nawaratwrn#p/a/u/2/BdjCL_4ItLA

Finally, to comment the condition of the experiment as it was retrieved, the MAIN payload had suffered major destruction, including: collapse of the structure and dismemberment of the line guide mechanism. However, it is clear from the entire flight footage that the camera, mounted to the bottom structure, was perfectly in place until the very last minutes of flight, and hence the collapse of the structure occurred either during the crash of the gondola or during its transport back to ESRANGE. Furthermore, the destruction of the line guide mechanism occurred during transport back to ESRANGE because the dismantled parts were lying in the truck, and were not picked up from the ground at the crash site. This destruction is then concluded to be attributable to the vibrations experiences during transport,



which has the well-known tendency to loosen screws and other fixtures which were not designed and built to withstand such conditions.

Several steps were taken to extract the MAIN payload from the gondola upon retrieval. First, the top insulation panel was taken off as it bared no load. Then, it was possible to support what was left of the structure with a crane. Once the structure was secured, we were able to sequentially and carefully remove the side insulation panels, revealing the damage to the internal systems. Despite the collapse of the structure and the dismantling of the line guide mechanism, most of the components were intact, at first visual inspection, only the reel motor had a weakened contact which eventually broke off while handling it, but this is also highly suspected to be due to crash or transport as there is no evidence that this connector could have been damaged during flight. Then, the whole payload was taken off the gondola and brought to the team's workbench. There, the team were finally were able to get a closer look at the components and found the only evidence of failure on the reel itself, and thus, it was taken off the payload and examined. The next subsection presents the analysis of the reel's inspection.

8.9.3 Line Failure Analysis

The failure of the experiment was essentially due to the line which broke. Initial inspection of the reel and the remaining line showed two obvious facts: the line broke and it broke before it ran out. What is not so obvious and still remains somewhat of a mystery, is why it broke. As seen from all of the following figures, the line broke at two places, at the end going to the FISH and at the end that was attached to the barrel of the reel.

Firstly, the breakpoint of the line on the bail will be analysed. As seen from Figure 8.14, the line was literally stuck on the bail, almost incrusting in the metal of the bail. Also, there were several fragments of the line visible on the bail as well as several dents which were not present pre-flight. This is a witness to the extreme frictional events that occurred when closing the bail. The fact that several dents and fragments were present on various parts of the bail corroborates with the audio recordings which suggest through violent impact sounds that the line jumped from places to places on the bail as it was being forced shut. It is of course hard to determine why the line would be subject to such discontinuous jumps, but one possible cause would be the snagging of the line on itself which would make the effect of the brake of the reel somewhat discontinuous.

Secondly, the breakpoint of the line at its interface to the reel barrel is also of interest. Pre-flight, the line was manually and carefully attached to and wound on the barrel. We also know from the flight data that the reel was, to our best knowledge, at a temperature between 5 and 10 degrees Celsius which virtually rules out thermal contraction of the barrel. Still, for the line to have broken at its attachment point requires the propagation of the tension all the way to the attach point. This is surprising as one would expect the tension to tighten the line on the barrel and thus firming the grip on the barrel which should absorb the tension.



However, this was clearly not the case from the evidences. One remark to be made, however, is that the attachment point of the line on the barrel was through these holes in the barrel which had sharp corners and hence the tension required on the line to make it break is expected to be low.

Thirdly, the inspection of the line itself as it was wound on the barrel after retrieval shows a large amount of snagging. As seen from Figure 8.18, the line, even the parts close to the barrel, was significantly snagged and compressed as well as physically damaged. As mentioned before, the line was carefully wound on the barrel pre-flight with the explicit intention of avoiding that very same issue. However, it is clear that it was not avoided. The line being snagged on itself can have some obvious consequences. As mentioned earlier, it can cause discontinuities in the force applied by the reel brake and hence cause some jumping and impact-type forces on the bail which could explain the violent sounds heard in the audio recording. Also, the tension build-up on the line, when snagged, will further the damage to the line itself rendering it weakened and prone to failure.

Finally, as much as can be concluded about the possible cause of the failure of the line, we can formulate the following hypothesis based on the physical evidence. As the tension on the line was created from forcing the bail shut, probably early on, the interface to the barrel most have worn out and broke, then, the tension build-up could have resulted in increased snagging and damage to the line still wound on the barrel. In turn, the increased snagging could have made the force pattern on the contact between the line and the bail more discontinuous and characterized by several impacts rather than a more gentle continuous force. Finally, those repeated impacts caused dents on the bail and pieces of line to wear off on the line until eventual, a section of line, weakened by the intense snagging, broke off completely, letting the FISH continue its fall.

Although the above seems like a reasonable hypothesis to us since it can be corroborated with all our evidence, the evidence is not sufficient to prove that this was the way the events unfolded. It does seem, however, to be the simplest explanation, one which does not involve any far-fetched theories. We have nevertheless debated on several other possibilities or contributing factors, but none really have enough evidence to soundly support them. One such example is the consideration that the absence of convection could have made the heat dissipation process at the line-to-bail contact much different during flight than during our system tests, it could have burned the line, causing the weakness, and melted the metal of the bail, causing the dents observed. This is only one of the many speculations we have made post-flight, however, although interesting theories, it would be unscientific to put forth those theories without enough evidence to confirm them. This is why we have settled for the aforementioned conclusion about the failure of the line because it is, for the most part, a directly based on our observations.

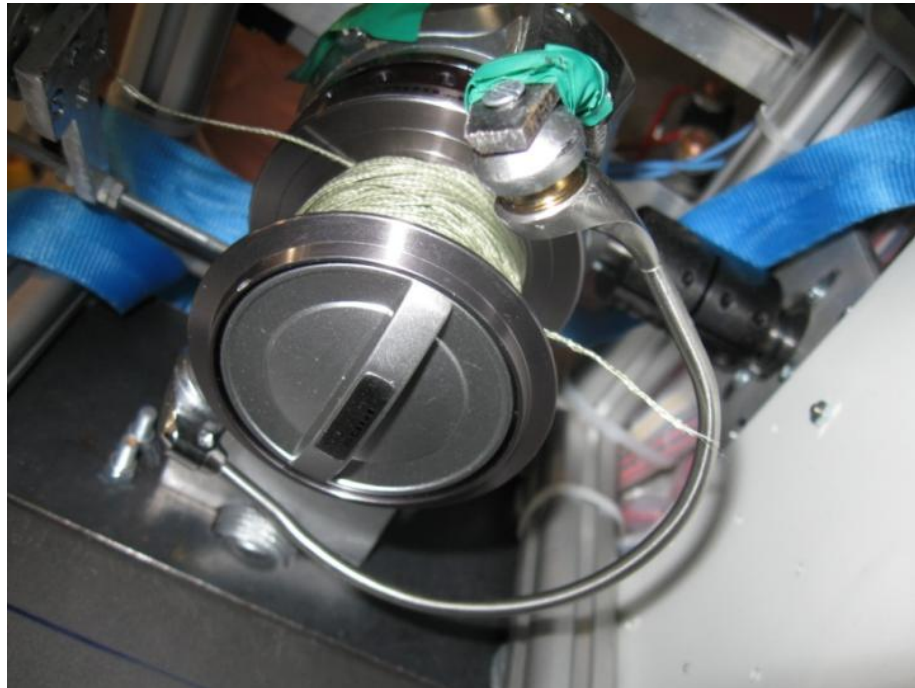


Figure 8.13 Picture of the Reel as it was when recovered after flight



Figure 8.14 Close-up of the broken line as it was stuck on the bail when recovered



Figure 8.16 The Reel Barrel after unwinding most of the remaining line, showing signs of snagging of the line as well as a better view of the failure of the line near its interface to the reel



Figure 8.17 Picture of what remained of the line interface to the reel

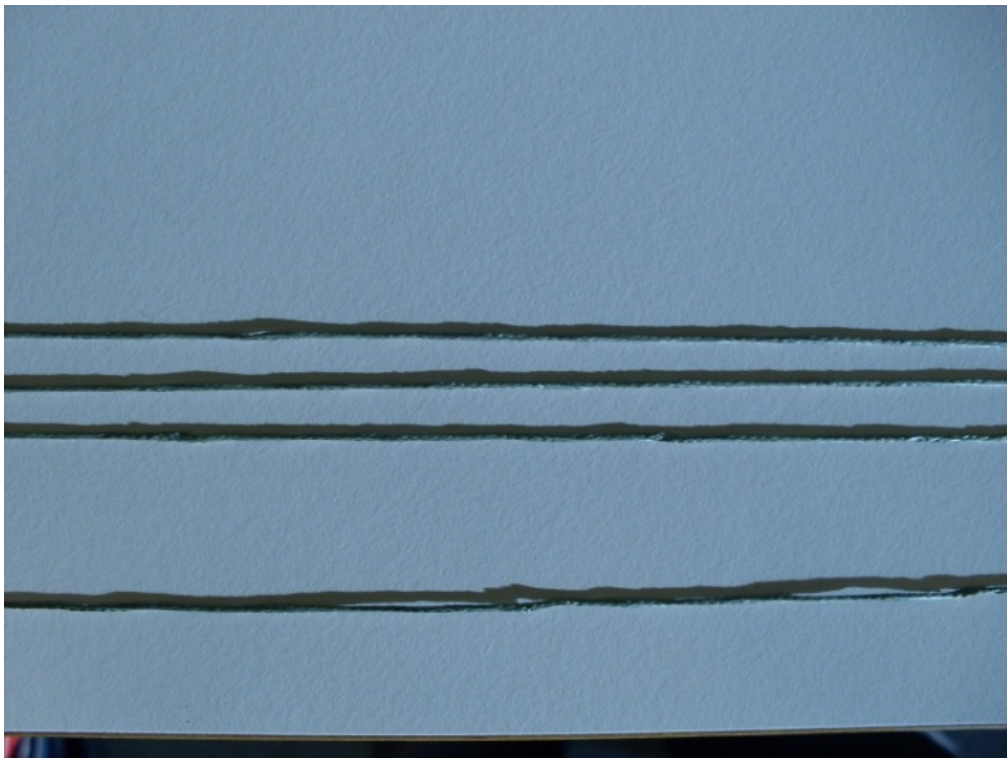


Figure 8.18 Examples of the snagging evidence on the line



8.10 Results

Due to the loss of the FISH, multiple drops were not able to be performed. Thus reliable flight acceleration data was not acquired. A software version error found immediately prior to launch and therefore unable to be fixed was that the system was not able to receive on the ground station the data in the 'high data rate mode' used during the drops. Therefore, all the acceleration data from the one drop that occurred is stored on the FISH and was not transmitted to the ground station. However, data from temperature feedback sensors demonstrated the operation of the system, as did the IP camera video and audio outputs. This is in addition to the acceleration data from the FISH that was received before the drop sequence, demonstrating operation of the on-board FISH systems and communication protocols.

8.10.1 Flight Temperature Data

During the flight, the temperature of the MAIN Payload was measured through temperature sensors that were placed on key components. This consisted of temperature reading from the motor controller, the microcontroller, the reel, the battery and the line guide. The corresponding data is shown in Figure 8.19

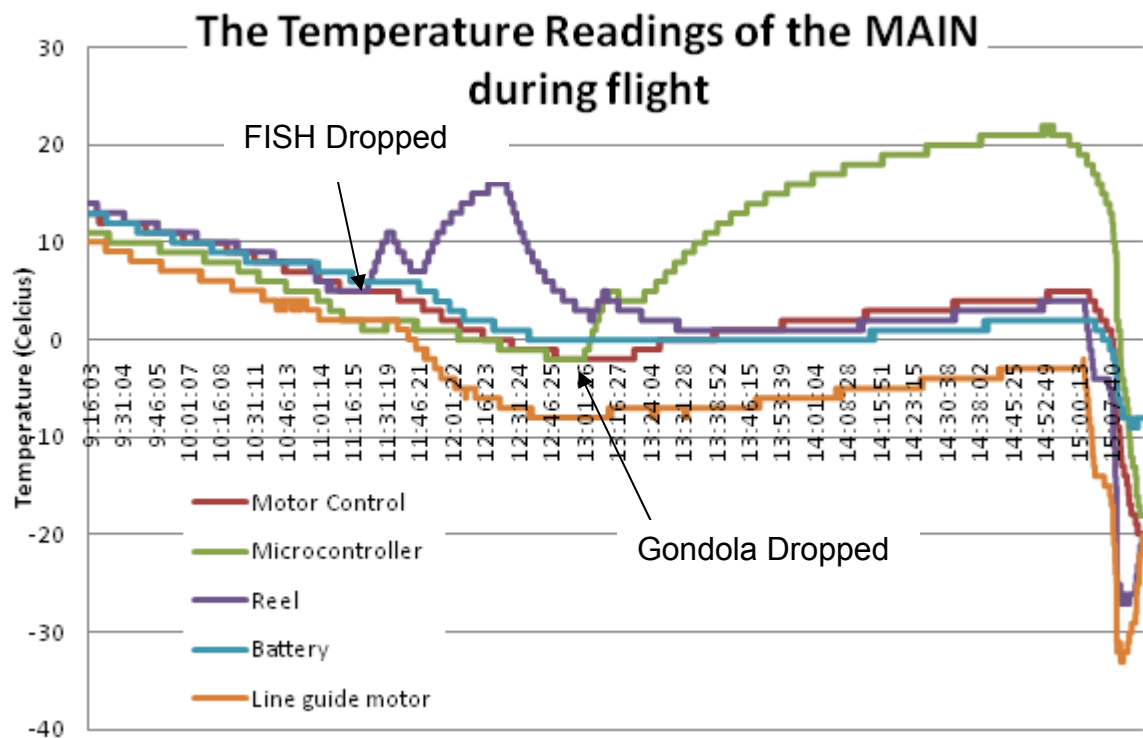


Figure 8.19: Temperature Reading of the MAIN during flight

The balloon was launched approximately at the beginning of the dataset thus all the temperatures start to decrease. The initial temperatures are high as a result of the insulation plug used to close the hole at the MAIN Payload base and chemical heaters used until last access. The FISH was dropped at the indicated position in which the reel was used. There are two spikes in the reel temperature, corresponding to the two periods of reeling up that were implemented following the drop, with the second being longer than the first. The gondola was dropped at the time indicated on the graph and thus the temperature of all devices increased due to the heaters adding energy to the system. The values started becoming inaccurate when the batteries start to run out, as is indicated via all values decreasing.

This figure also shows that all devices measured were kept at their operational temperatures for the duration of the flight which verifies requirement Req T.M.1. This was successful due to the active and passive heating that was present during the whole flight, and the measures taken to ensure the system stayed warm on the launch pad.

8.10.2 Flight Acceleration Data of the FISH prior to the Drop

One of the hypotheses for the line breaking during the drop was that the gondola had a significant vertical velocity when the mass was released thus adding an

extra force on the line causing it to break. A figure displaying the gondola altitude over time is shown in Figure 8.20.

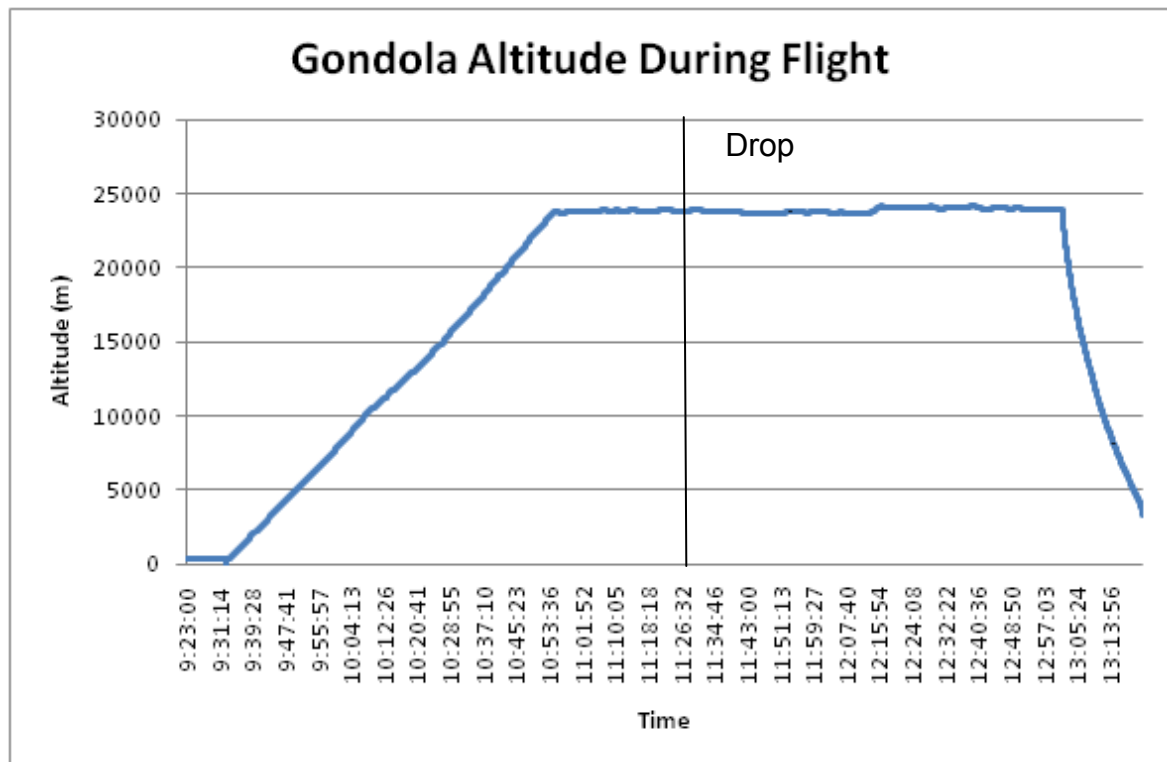


Figure 8.20: Gondola Altitude during flight

The altitude of the gondola shows no major deviations from its altitude when a drop was conducted, which is easier to see in Figure 8.21 where the graph is zoomed in on the time the drop was commenced. The time of the drop was calibrated via the launch time recorded by the team members computer watches and that of the initial data. This could have an approximate uncertainty of about 30s but no sharp spike in the altitude is observed either side of the estimated drop time, which could otherwise have caused an increased stress on the line through increasing the reeling speed of the line off the spool. Thus the loss of 1.6kg from the 100kg gondola shows no significant variation of the altitude and so it was concluded that the motion of the gondola did not contribute to the line breaking.

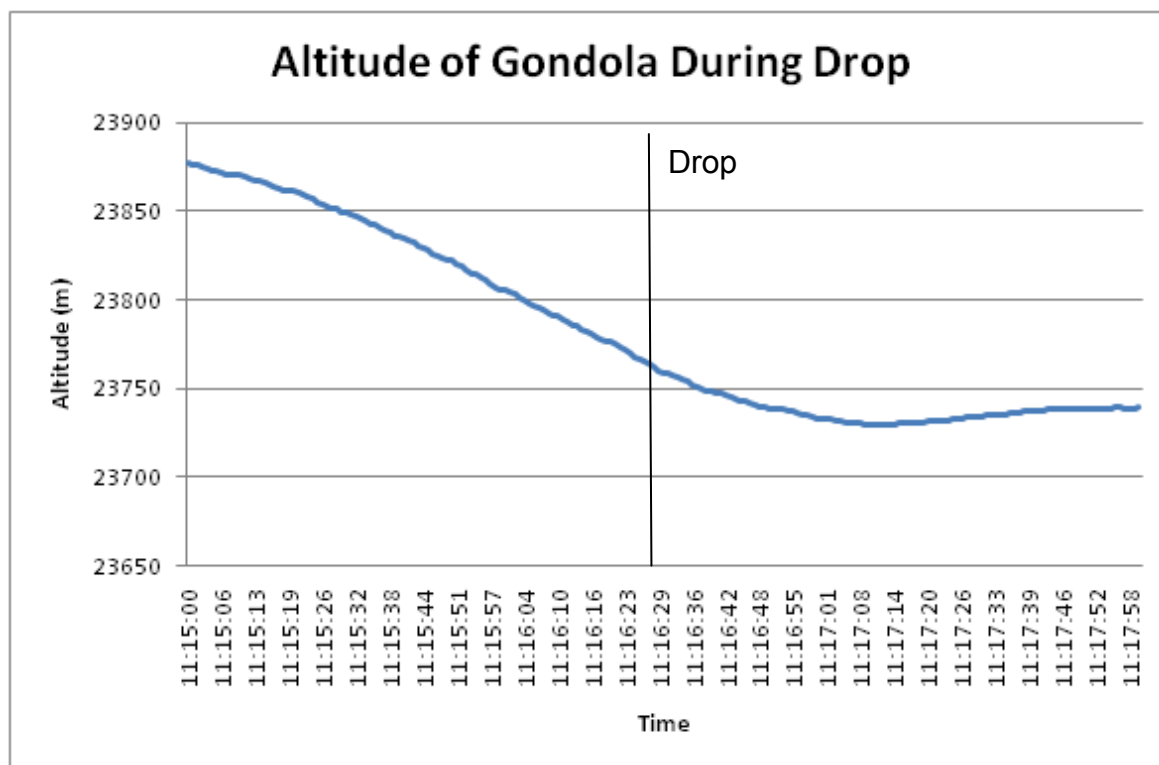


Figure 8.21: Zoomed in version of the Gondola Altitude during the Drop time

8.10.3 FISH Data

Due to the loss of the FISH on the first drop and the high data rate mode for the communication between the FISH and the MAIN not working due to a software version error, no data was collected from the FISH during the drop. Thus no analysis of the drop mode was conducted or discussed. Accelerometer, temperature and gyroscopic data from the FISH was recorded on the ground station and MAIN Payload SD card, prior to the drop, demonstrating that the FISH was operational. This data appears to be corrupted or encoded, and has not yet been able to be decoded into useful values despite numerous attempts by various team members. This process is a work in progress. The data is listed in Appendix 1. This data would be useful to analyse with respect to the gondola motion to determine the motion of the FISH below the gondola and the dynamic relationship between the two bodies.



8.11 Lessons learned

Many lessons were learned over the reel.SMART project, both through the workshops and design reviews as well as through the project life cycle and technical development.

The team learned that the establishment of detailed requirements for the system and subsystems was integral in defining project scope and was able to utilise this successfully, sticking to the requirements of the project from the PDR stage. Requirement verification was used to guide the testing plan and a verification table that was constantly updated to monitor progress was found to be valuable indeed. Furthermore, establishing a key list of functionalities was important and allowed for milestones to be recognised and reached.

Project resources of time and budget were critical, and this was shown to necessitate prior planning and action plans for overshooting these margins, which were difficult to develop when working to full capacity. When the 'red line' was reached, the team invested even more of their own time and funds to keep the project going, demonstrating their commitment to the project. The team also learned about how to source key components and how to factor in lag-time in the shipping of goods.

The challenges of a group spread across different countries, time-zones and cultures presented many challenges. However this also provided a richness to the team and valuable experience in working with different nationalities. It demonstrated how challenging constant and effective communication can be, and also its necessity.

Technically, the initial approach of the team to 'keep it simple' was decided. However, factoring in a significant amount of redundancies and functionalities caused much of the design to become increasingly complex. Thus a key learning point was to keep the design as simple as possible, whilst keeping space for further add-ins and modifications as required. The Electrical subsystem learned that prototyping is important in addition to working from datasheets, and the Software subsystem learned to coordinate closely with electrical to begin integration as early as possible and found the use of evaluation boards to program and test software early was invaluable. The Mechanical subsystem learned to conduct tests as early as possible to find failures in the design and to allow time for testing failures and redesign. Also, they learned how to effectively use the majority of time on the critical issues. Overall, the team learned that subsystem designs must be built, constructed and tested as early as possible, as it is easy to underestimate the time and resources required for integration and system testing. The team has thus learned that where possible, system testing should be considered as the highest time consuming factor as design iterations are almost

always necessary, even if individual subsystems are proven to work on their own. All team members also learned copious amounts technically both within and outside their areas of expertise.

Overall, this project has been an incredibly valuable learning experience, both technically, personally and professionally. It has provided the members of reel.SMRT with the experience of coming up with their own original project and developing it through all of the project phases – a rare opportunity. This has included such factors as learning about design reviews, presentations and documentation for companies and space agencies in addition to being involved in a professional launch campaign. Extremely challenging and at many times exhilarating with the pace of problems presented and solutions invented, this project was one that will benefit each team member for years to come. We have truly learned an incredible amount.



Figure 8.22 Team members at launch week, Left to right: Jan Speidel, Campbell Pegg, Nawarat Termtanasombat, Katherine Bennell, Mikael Persson and Mikulas Jandak.



9 CONCLUSION

The reel.SMRT project was a challenge taken on by seven postgraduate university students from the SpaceMaster programme. From the conception of the idea and objectives, through multiple design iterations and reviews, construction, testing and the flight and beyond this was an extremely worthwhile learning experience. Although full functionality was not achieved, the team are satisfied and proud of their efforts and performance in addressing their complex and demanding question.

The reel.SMRT system was fully functionally tested and flew on-board BEXUS-09 in October 2009. All performances were verified during the integration as working and this was repeated by a test at short access before launch, except for a small software bug. During the flight, the line guide was unreeled, the dropped payload was reeled up and then a drop was successfully performed. Due to an unforeseen even during the flight, most likely due to snagging or thermal effects not made evident through testing, the line broke at a critical connection point as a result of the forces during the first drop and therefore the FISH was not able to be reeled back up. Following the drop, the line guide was able to be locked and the line reeled up. All other systems were thus fully operational and demonstrated a significant number of functionalities.

When the gondola was returned, a thorough investigation was performed on the experiment. The IP camera's steady position and unobstructed view demonstrated that the structure retained its integrity throughout the flight phase until the connection ended just before landing. Therefore, due to landing forces or rough transport back to ESRANGE, several critical construction screws dislodged despite the use of lock-tight. This thus made narrow point of fault analysis almost impossible. However, the line perforation indicated an abrupt cut-off of the line, supporting the hypothesis of the breakdown of this critical connection point.

Despite not achieving full functionality, the reel.SMRT experiment demonstrated that a low gravity platform utilising a tethered dropped payload is theoretically possible and could operate a drop in the harsh environment of the stratosphere. The system, however, is unable to provide a measure of the quality of the reduced gravity until the dropped payload and its acceleration data is recovered. This data would prove to be most interesting, providing acceleration data throughout the drop as well as the free-fall through the atmosphere to the ground. With this data, the objectives of the feasibility analysis may ultimately be met. Nevertheless, the outcome of this experiment led to the following conclusions:

- The video capture of the flight suggests good stability of the capsule as it hangs below the gondola.



- The flight video in tandem with the integration tests shows that the spinning reel design is very good and fairly repeatable for dripping a capsule in near-freefall conditions multiple times.
- The design as it stands is fully operational for the reeling operation, for lowering and raising payloads from a balloon.
- Commercial fishing equipment is not strong enough for even a minimum weight capsule for dropping operations: a custom design is necessary.

Thus the partial success of all subsystems shows that the functionality of the designed system was achieved and that the ultimate feasibility of low-gravity experiments onboard balloons could perhaps be proven by a sturdier custom redesign of the reel.SMRT system. For higher payload masses the implementation of an up-scaled system would be necessary. Recommendations for customisation, particularly pertaining to the drop mode, include:

- A sturdier bail and reel mechanism.
- A higher strength line that is resilient to multiple drops, such as a larger diameter *Dyneema*TM line.
- A mechanism to hold the FISH in place prior to the drop would optimise stability in the horizontal axis.
- A means to transfer power to the payload would enable lower mass for experimental payloads.
- A dynamic analysis of the balloon during the drop for a larger mass payload and system would be valuable.
- A greater level of performance and control could be obtained through use of a variable braking mechanism, which may be achieved through interfacing a motor to the variable brake of, for example, a mechanism akin to that within a spinning fishing reel.
- For long drops (on the order of kilometres), the line speed off the reel is limiting and alternate methods may be required, such as a single drop of slack line. Such a system might include a spinning reel with a pinched-in base, allowing the line to fall off it under gravity.





10 ABBREVIATIONS AND REFERENCES

10.1 Abbreviations

AC	Aerodynamic Centre
AIT	Assembly, Integration and Test
ASAP	As soon as possible
BO	Bonn, DLR, German Space Agency
BR	Bremen, DLR Institute of Space Systems
BSD	Berkeley Software Distribution
CAD	Computer Aided Design
CDR	Critical Design Review
CoG	Centre of Gravity
DC	Direct Current
DLR	Deutsches Zentrum für Luft- und Raumfahrt
EAT	Experiment Acceptance Test
EAR	Experiment Acceptance Review
EBASS	Balloon Piloting System
EGon	ESRANGE Balloon Gondola
EIT	Electrical Interface Test
E-Link	Ethernet up & downlink system
EMC	Electro-Magnetic Compatibility
EPM	ESRANGE Project Manager
ESA	European Space Agency
ESRANGE	European Sounding Rocket Launching Range
ESTEC	European Space Research and Technology Centre, ESA
ESW	Experiment Selection Workshop
FAR	Flight Acceptance Review
FEA	Finite Element Analysis
FISH	Free-falling Instrument System Housing
FS	Factor of Safety
FST	Flight Simulation Test
FRP	Flight Requirement Plan
FRR	Flight Readiness Review
GNU	GNU's Not Unix
GPS	Global Positioning System
GSE	Ground Support Equipment
HARVE	High-Altitude Reduced-Gravity Vehicle Experiments
HK	House Keeping
H/W	Hardware
ICD	Interface control document
IMU	Inertial Measurement Unit
IP	Internet Protocol
I/F	Interface



IRF	Institutionen för Rymdfysik
IRV	Institutionen för Rymdvetenskap
LAN	Local Area Network
LT	Local Time
LOS	Line of Sight
LTU	Luleå Tekniska Universitet
LRR	Launch Readiness Review
Mbps	Mega Bits per second
MFH	Mission Flight Handbook
MORABA	Mobile Raketen Basis (DLR, Eurolaunch)
MTR	Mid Term Report
NYA	Not Yet Applicable
ODE	Open Dynamic Engine
OP	Oberpfaffenhofen, DLR Center
PCB	Printed Circuit Board
PDR	Preliminary Design Review
PFR	Post Flight Report
PST	Payload System Test
RTOS	Real Time Operating System
SDK	Software Development Kit
SED	Student Experiment Documentation
SM	SpaceMaster
SMRT	SpaceMaster Robotics Team
SNSB	Swedish National Space Board
SSC	Swedish Space Corporation (Eurolaunch)
STW	Student Training Week
S/W	Software
T	Time before and after launch noted with + or -
TBC	To be confirmed
TBD	To be determined
TKK	Teknillinen Korkeakoulu
UHMWPE	Ultra-High Molecular Weight Polyethylene
WBS	Work Breakdown Structure
xgravler	Experimental Gravity Research with Lego-Based Robotic



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11 APPENDICES

(Attached Documents)

- Appendix 1 System Level
- Appendix 2 Management
- Appendix 3 Electrical Subsystem
- Appendix 4 Software Subsystem
- Appendix 5 Mechanical Subsystem
- Appendix 6 Outreach



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